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Climate change, natural disasters and adaptation investments: Inter- and intra-port competition and cooperation

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ABSTRACT

This paper investigates disaster adaptation investments made by two ports competing for shippers in a common hinterland. Each port is a landlord type, consisting of a port authority and a terminal operator that both maximize profits. The probability of a natural disaster, which is related to climate change, is ambiguous at the start of an adaptation investment (Knightian uncertainty), but will be known after the lengthy investment. We examine the impacts of such Knightian uncertainty, inter-port and intra-port competition and cooperation on the port adaptation investments. We find that a high expectation of the disaster occurrence probability encourages port adaptation, while a high variance of the disaster occurrence probability discourages port adaptation. Furthermore, inter-port competition results in more adaptation investments (the "competition effect"), whereas within a port there is free riding on adaptation between the port authority and the terminal operator (the "free-riding effect"). We further extend our analysis to public port authorities that maximize social welfare, and find that the competition effect on port adaptation still exists but the free-riding effect is no longer present. As a robustness check, a Poisson jump process is also used to model disaster occurrence at the operation stage. We find, with this Poisson assumption, the effects of Knightian uncertainty on port adaptation still hold.

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1. Introduction

The past decade has witnessed more frequent extreme weather events and natural disasters around the world, with increasing economic and social costs. The examples include hurricanes and storms in recent years (e.g., Sandy in 2012 and, most recently, Harvey in 2017, on the United States coastline). For instance, Harvey brought an estimated economic loss of \$125 billion,[1] whereas Sandy caused an estimated \$70.2 billion loss (the United States National Hurricane Center).[2] Scientific studies suggest that climate change may lead to an increase in both the occurrence and the strength of weather-related natural disasters in the near future (e.g., Keohane and Victor, 2010; Min et al., 2011; IPCC, 2013). According to Morgan Stanley research, of the top-ten most costly hurricanes hitting the United States (US) until 2015, eight occurred in this century.[3] Such increasing frequency and strength of hurricanes in North Atlantic Basin is due, at least in part, to global

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[1] Unless specified otherwise, the dollar amount in this paper refers to US\$.
[2] Please see the link for details: https://weather.com/storms/hurricane/news/2018-01-29-americas-costliest-hurricanes.
[3] The details about the top-ten hurricanes can be found at http://www.businessinsider.com/hurricane-irma-costliest-hurricanes-us-history-map-2017-9.

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warming and related temperature rise of the ocean (IPCC, 2013). The global warning largely increases the risk of coastal and marine natural disasters (in terms of frequency and intensity) around the world. By the end of this century the average sea level may be 0.75-0.80 meters higher than today's level (Schaeffer et al., 2012). Global warming and associated sea-level rise (SLR) can bring about more frequent and intense wind, freshet flooding and complex tide waves (IPCC, 2013; OECD, 2016).

Seaports are highly vulnerable to coastal and marine natural disasters, and are exposed to climate hazards. For example, Nicholls et al. (2008) assessed the exposure to flooding for 136 large port cities around the globe. Stenek et al. (2011) and Scott et al. (2013) gauged the vulnerability for port system sub-components to climate change, including navigation, berthing, material handling, vehicle movement, goods storage and transportation. The increasing risk of natural disasters to seaports may trigger substantial social and economic loss and, in particular, lead to shifts in freight transport and passenger flow (Koetse and Rietveld, 2009). Many ports play a critical role in global supply chains, so that any significant loss or degradation of service due to these disasters would have significant knock-on effects on global supply chain performance (OECD, 2016).

Unlike the rich literature on environmental effects of transportation (especially the mitigation of transport sector to climate change; see, e.g., Zhang et al., 2004; Wang et al., 2015), there is a lack of theoretical research on adaptation of maritime transport to climate change-related disasters.[4] One exception is Xiao et al. (2015) who modeled seaport adaptation investments by both port authority and terminal operator under the uncertainty of disaster occurrence. They found that there is a free-riding effect of adaptation efforts for the port authority and terminal operator, and that information about the disaster occurrence is essential for the optimal timing of adaptation investments (the "invest now or later" question). It is noted that Xiao et al. (2015) considered port adaptation of a single port and so they did not consider inter-port competition.[5] They further treated port demand and pricing being exogenous to adaptation investments. Nevertheless, port adaptation and resilience to natural disaster can affect a port's competitiveness vs. neighboring ports. For instance, port disruption can cause serious reputational and direct economic losses on shippers (Zhang and Lam, 2015), leading to their switching to a better adapted port for services (Chang, 2000).[6] Therefore, an improved theoretical model on port adaptation need to endogenize the shipper's demand and port pricing decisions, and incorporate the inter-port competition as well.[7]

Furthermore, despite a rich theoretical literature on traffic demand uncertainty modeling,[8] uncertainty about climate change-related disasters and the associated costs have not been well modeled in existing maritime transport studies. Uncertainty regarding their occurrence and outcomes can be very high (IPCC, 2013; OECD, 2016), due to limited scientific knowledge and to forecast complexity. In contrast, traffic demand can be more accurately forecasted with the availability of rich historical traffic data and other economic and demographic variables. Therefore, to model uncertainty of climate change-related disasters, one needs to account for the large ambiguity at the adaptation planning and investment stage, noting that adaptation projects usually are lengthy in duration and very costly. Xiao et al. (2015) modeled the disaster uncertainty in a two-period setting, assuming a uniformly distributed disaster occurrence probability in the first period but, with information learning, a more accurate (a more narrowly-bounded uniform distribution) probability in the second period. There is thus an option value in delaying investment, owing to better information about the disaster occurrence probability. However, this assumption of uniformly-distributed disaster occurrence probability could be restrictive. In this paper, we propose a model allowing a general distribution of the disaster occurrence probability, which can capture the "ambiguity" notion of disaster uncertainty that is absent in Xiao et al. (2015).

Taken together, the present paper contributes to existing literature by developing a more general analytical framework to analyze port adaptation to climate change-related disasters. More specifically, we model the climate change-related disaster occurrence probability to have Knightian uncertainty (Knight, 1921) at an early adaptation investment stage when two ports make adaptation decisions. Knightian uncertainty refers to ambiguity in which a decision maker must make decisions when the relevant probabilities are unknown. This is used to capture the fact that the probability of disaster occurrence is very

[4] There are a number of studies on post-disaster relief, and transport and logistics system resilience (e.g., Chen and Yu, 2016; Huang et al., 2013; Rawls and Turnquist, 2010; Sheu, 2014), but studies on adaptation strategies are relatively few. Further, the adaptation studies mainly adopt engineering approaches to an analysis of optimal cargo flows so as to enhance resilience of the supply chain or network. Economic-based strategy and policy analysis is rare, however.

[5] Recently, port competition and cooperation were also analyzed in the context of disaster prevention by Liu et al. (2018b), in which the ports can be either substitutes or complements with each other. They focused on the case of mitigation rather than adaptation, however.

[6] For example, Chang (2000) empirically studied the impact of the 1995 Great Hanshin earthquake on the port of Kobe (Japan), which was shut down post the disaster and only recovered after two years. She found that due to the earthquake damage, the Kobe port lost most of transshipment cargo to competing Asian ports, in both the short- and long-term.

[7] Theoretical analyses on port competition and the interplays between ports and their hinterlands are emerging. Wan et al. (2018) reviewed recent theoretical studies in the area, and found that these studies mainly focus on the port and hinterland capacity investments, and on port congestion pricing (De Borger et al., 2008; Zhang, 2008; De Borger and Proost, 2011; Luo et al., 2012; Wan and Zhang, 2013; Yuen et al., 2008). Some recent studies discussed the emission control of marine transport, such as Homsombat et al. (2013), Wang et al. (2015), Sheng et al. (2017) and Dai et al. (2018). However, none of these papers have considered port adaptation to climate-change risks.

[8] See, for example, the studies by Kraus (1982), D'Ouville and McDonald (1990), Proost and Van der Loo (2010), and Xiao et al. (2013). Kraus (1982) considered highway pricing and capacity choice under demand uncertainty, and found that both capacity and price are greater than those under an expected value of demand. D'Ouville and McDonald (1990) also studied the optimal capacity and toll of urban highways under demand uncertainty, and found that a social planner who simultaneously chooses the capacity and congestion toll to maximize the expected welfare will choose a larger capacity relative to the mean level of road use. Proost and Van der Loo (2010) examined capacity choice by modeling a social planner's decision on transport infrastructure capacity when the future demand can be either high or low, with different tolls being set for each case to maximize welfare. Xiao et al. (2013) analyzed the effects of demand uncertainty on airport capacity choices.

uncertain (is subject to a probability distribution) at the adaptation planning stage. Our Knightian uncertainty is general and covers a wider family of probability distributions of natural disaster occurrence, which are not limited to the specific assumptions in Weitzman (2009) and Xiao et al. (2015). The effects of this Knightian uncertainty on port adaptation are investigated. Moreover, the present paper will explicitly examine the impacts of both inter-port competition and intra-port cooperation on port adaptation by explicitly modeling the *endogenous* port pricing and shippers' demand together with port adaptation. It is the first paper, to our best knowledge, that analytically examines how inter-port competition would affect port adaptation.[9]

We find that, with the Knightian uncertainty assumption at the adaptation investment stage, port adaptation increases with the expectation of the disaster occurrence probability but decrease with its variance. In other words, a higher expectation of the disaster occurrence probability encourages adaptation investments, but the variance of the disaster occurrence probability can discourage adaptation investments. This analytical result provides an explanation for why in practice adaptation is much more difficult to implement than mitigation, as in practice the existing knowledge about climate change and associated disasters needed for adaptation is quite poor. Furthermore, when the port authorities maximize profits, inter-port competition results in more adaptation investments (relative to the absence of port competition), an effect we refer to as the "competition effect". On the other hand, there is free-riding on adaptation investments between the port authority and the terminal operator within a port, an effect we refer to as the "free-riding effect". The intra-port coordination can, by removing the free-riding effect, increase the adaptation investments. We further show that the competition and free-riding effects can be strengthened by a higher expectation, and a larger variance, of the disaster occurrence probability, and by a more intense inter-port competition.

We extend our analysis to public port authorities that maximize social welfare. In that case, the free-riding effect is shown to be absent; essentially, public port authorities are willing to invest more to account for the lower adaptation incentive by the private terminal operators. We also find that public port authorities lead to larger port adaptation, but not necessarily to higher expected welfare. This is because, without intra-port coordination, public authorities may invest excessively than the first-best level in order to overcome the lower adaptation incentive by private terminal operators. Finally, with alternative modeling of disaster occurrence following a Poisson jump process during the operation stage, we show that the port pricing and price difference between the competing and monopoly port authority decrease with the Poisson parameter. Without Knightian uncertainty in the Poisson parameter, port adaptation increases with the Poisson parameter at the operation stage. When the Poisson parameter has Knightian uncertainty at the adaptation investment stage, our previous findings still hold.

The paper is organized as follows. Section 2 sets up the basic model and introduces the notion of Knightian uncertainty of disaster occurrence for the two-port system. Section 3 derives the analytical results for equilibrium port adaptation with different inter-port and intra-port conditions. Section 4 examines the effect of inter-port competition intensity on port adaptation investments. Section 5 extends our model to account for public, welfare-maximizing port authorities and benchmarks the results with those of earlier sections with private port authorities. In Section 6, a robustness check is conducted by considering an alternative stochastic process, namely, a Poisson jump disaster occurrence. Section 7 contains the concluding remarks.

2. Basic model

We consider two nearby ports sharing a common hinterland that are subject to a threat of common but uncertain disaster (Fig. 1). The ports are of the landlord type: each port consists of one port authority owning basic port infrastructure, and a terminal operator as a tenant owning port superstructure and directly handling cargo transport (Liu, 1992).[10] The port infrastructure includes the port land, cannals, berths, basins, and storage areas, while the superstructure mainly includes cranes, pipes, and office buildings. The landlord port is the predominant type of ports in the world (e.g., Becker et al., 2012; Xiao et al., 2015). For a landlord-type port, the terminal operators are private entities. For example, PSA International, Hutchison Port Holding, APM terminals, DP World and China Merchant Holding are the major terminal operator companies operating around the world.[11] In our analysis below, port authorities are first assumed to be private entities that maximize profit, similar to Chen and Liu (2014) and Liu et al. (2018a). This consideration is relevant, as privatizing port authority from public sector has gradually become a worldwide trend since the 1990s, aiming to relieve government's heavy financial

[9] Different from Xiao et al. (2015) with a multi-period investment model, the present paper abstracts away the issue of adaptation investment timing (the option value to choose to invest early or late).

[10] There is no universally accepted framework for port classification. A widely adopted classification is by Liu (1992), which categorizes a port into four types: service port, tool port, landlord port and private port. A service port is a port when the port authority is responsible for the provision of all port facilities; a tool port is when the port authority is public and provides the infrastructure and superstructure, while the provision of services is licensed to private terminal operators; and a landlord port is a port in which the domain of the port authority (public or private) is restricted to the provision of the infrastructure, while investment in the superstructure and port operation lies in the responsibility of licensed private companies. Finally, a private port is when the provision of all the facilities and services is left to one single private entity.

[11] We note that one operator may operate in two nearby ports at the same time (for example, Hutchison Port Holding operates in both Hong Kong and Shenzhen ports). One port can also have multiple terminal operators. To make the model tractable and to focus on our main trade-off issues, we consider that there is only one terminal operator at each port and that the two operators are independent.

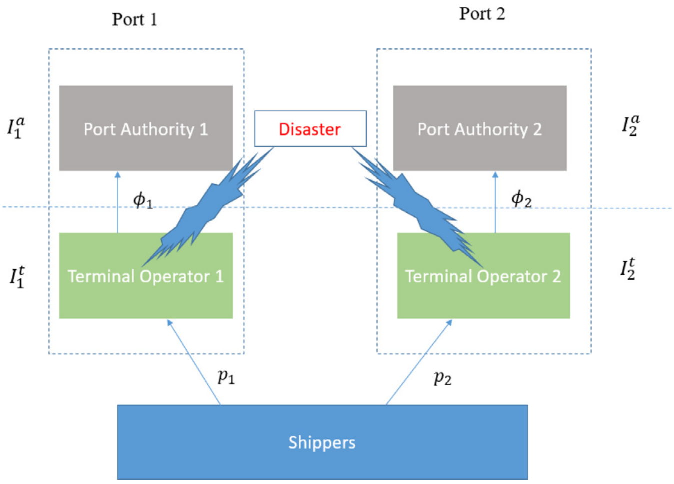

Fig. 1. The market structure of the two-port system.

burden and to upgrade port operation efficiency (Liu, 1995; Cullinane et al., 2005).[12] Even without full privatization, many port authorities today have been corporatized, with government controlling partial share. Meanwhile, port governance has also been transferred from the national/state governments to local ones who are responsible for port financial performance (Cheon et al., 2010).[13] As a result, the port authorities would be profit-oriented, at least to a certain degree. In Section 5, we will extend our analysis to the case of public port authorities that maximize social welfare.

The two ports under consideration may belong to competing port authorities. Such inter-port competition is exemplified by China's Pearl River Delta, with Hong Kong port competing against Shenzhen port to serve the market of southern China. The other example is the Hamburg-Le Havre (HLH) port range with several ports competing as gateways to West and North Europe. Alternatively, we often observe the cases with a single port authority controlling multiple ports. For example, Port Authority of New York and New Jersey controls the Port of Newark, Port of Perth Amboy and Port of New York. Georgia Ports Authority controls the Port of Savannah and Port of Brunswick on the east coast of the US.

For a landlord port, the port authority signs concession contracts with the private terminal operator, stipulating the duration, concession fee scheme and other terms when leasing the port land and basic facilities to the operator (Trujillo and Nombela, 2000). Notteboom (2006) summarizes common types of concession contracts between the port authority and terminal operator. While detailed concession fee schemes vary among ports, commonly the port authority charges a concession fee to the terminal operator based on the throughput it handled, i.e., a unit concession fee, such that the total concession fee is proportional to the cargo volume.[14] Analogous to Basso and Zhang (2007),[15] it is assumed that the service charges within a transport facility are determined in a "vertical structure": In our context, the port authority (as the upstream landlord) decides a unit charge (unit concession fee) onto the terminal operator (as the downstream tenant) first, and then the terminal operator chooses its unit service charge to be paid by shippers.

We will examine the impacts of inter-port competition and a monopoly port authority, and intra-port cooperation between the port authority and terminal operator within one port, on port adaptation. [16] A multi-stage game is used to model both an "adaptation investment stage" for the ports, and an "operation stage" when the port charges are determined, conditional on the adaptation investments.[17] The timeline of the model is given in Fig. 2. We assume the disaster occurrence to be a Bernoulli trial at the operation stage with occurrence probability x. The probability of disaster occurrence x is as-

[12] Port authority privatization was pioneered by the UK Thatcher's government in the 1990s (Baird and Valentine, 2006). Later, corporatization of port authorities has been widely applied in other parts of the world, especially in Asia and Oceania (Everett, 2005; World Bank, 2001).

[13] According to Cheon et al. (2010), in 1991, 42% of the world's major hub and gateway ports were managed by national or state government bodies; by 2004, the percentage dropped to mere 32%. Corporatized port authorities accounted for less than 1/3 in 1991, but by 2004, the number became 45%.

[14] De Monie (2005) specified three most common port authority concession fee schemes: unit fee, fixed fee, and two-part tariff. Chen and Liu (2014) and Liu et al. (2018a) analytically discuss and compare these three schemes for a port authority to maximize profit. They find that unit fee is most likely to be preferred by a profit-maximizing port authority.

[15] Basso and Zhang (2007) studied rivalry between two congested facilities by considering the provider of the facility infrastructure as upstream, and the facility user (carrier) as downstream. The pricing is determined in a vertical structure with the downstream carrier charging the end consumer, while the upstream infrastructure provider charges the carrier.

[16] We appreciate anonymous reviewer to point out that the term "intra-port" is widely used to refer to horizontal relations among terminal operators within one port, instead of the vertical relation between port authority and terminal operator. In our model, we only consider one terminal operator within each port, thus the horizontal relation among terminal operators is abstracted away. Thus, the term "intra-port" is used to describe the vertical relation between port authority and terminal operator.

[17] A multi-stage game is a widely adopted approach to the modelling of capacity investment at an early stage and pricing at a later stage for transport infrastructure such as Luo et al. (2012) on ports and Xiao et al. (2013) on airports.

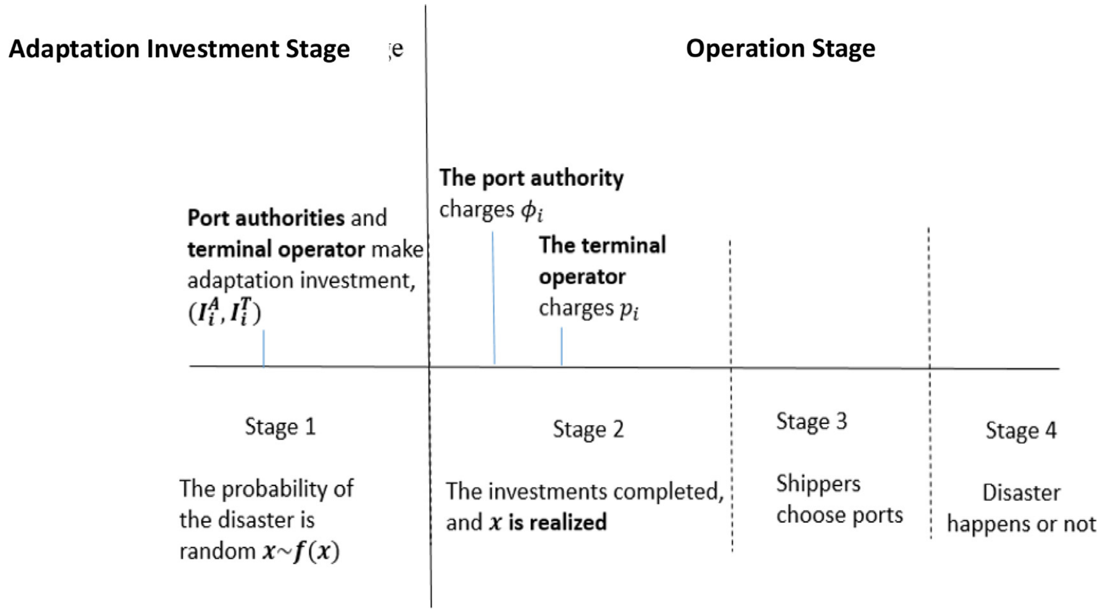

Fig. 2. The timeline of the decisions of different parties.

sumed to be ambiguous at the adaptation investment stage, which is a Knightian uncertainty (Knight, 1921; Camerer and Weber, 1992; Nishimura and Ozaki, 2007; Gao and Driouchi, 2013).[18] Knightian uncertainty implies that disaster occurrence probability x can be a random variable at the adaptation investment stage, with a probability density function (pdf) $f(x)$, the expectation Ω and the variance Σ. But this probability only becomes realized later at the operation stage when the ports decide price and the shippers choose a port. This improvement in information reflects a relevant setting in which a better knowledge on climate change and related disasters is accumulated during the lengthy period of adaptation investment.[19]

More specifically, at the adaptation investment stage, the port authorities and terminal operators of the two ports simultaneously determine their adaptation investment I_i^a, I_i^t respectively, which have an effect to protect shippers' cargo during a disaster (see more detailed discussion in the next paragraph). In general, port authorities and terminal operators can have different adaptation measures. Port authorities' adaptations to disasters (i.e., storms, flooding and strong wind) are mainly on basic port infrastructure, such as building breakwaters, storm barriers, flood-control gates, improving the drainage system, and elevation of terminal. These measures may not be specific to the protection of particular terminals (while benefiting the entire port). Terminal operators' adaptation is mainly for its own superstructure built on the port's infrastructure, such as berths and piers. They mainly adapt to disasters through redesigning, and retrofitting of the terminal facilities (Becker et al., 2012). Once decided, the adaptation investments are assumed to be fixed since any adjustment would require additional, complex evaluations and funding approvals, thus causing major delays in completion. We do not consider the case where the disaster occurs during the period of adaptation constructions. However, this does not alter strategic behavior of the ports since both port authorities and terminal operators do not adjust pricing until the port adaptation is installed.

At the operation stage, following Basso and Zhang (2007) and Wan et al. (2016), we adopt an infinite linear city model to derive shipper demand conditional on port service charges p_i and port adaptation investments I_i^a, I_i^t in response to disaster occurrence probability x (Fig. 3). The value to a shipper of using the port service V is exogenously given. Shippers choose which port to use before observing the disaster occurs or not.[20] If the disaster occurs, shippers will incur a damage as $D - \eta(I_i^a + I_i^t)$, where D is the damage level without any port adaptation, and $\eta(I_i^a + I_i^t)$ is the reduction of damage ow-

[18] As mentioned earlier, this ambiguity is due to limited knowledge available at the time of adaptation planning. Port authorities and terminal operators need to exert efforts to search for best estimates of disaster occurrence probabilities and conduct forecasting on disaster uncertainty. However, the best forecast at the investment stage can still be very inaccurate compared with information available at a later stage when the scientific research advances with better forecast during this lengthy duration of adaptation projects. For example, IPCC (Intergovernmental Panel on Climate Change), a UN entity, conducted comprehensive scientific research on climate change and predicted its outcome, such as SLR and temperature. It has published five reports in 1990, 1995, 2001, 2007, and 2013. The SLR and temperature projections in both the near term (2040-2060) and long term (2080-2100) have been updated every time with improved scientific models and better data collected.

[19] As for the Bernoulli assumption of disaster occurrence at the operation stage, while it is more tractable and facilitates our analysis, it restricts the operation stage as a static time point, which may not be very realistic. Later in Section 6, we thus extend our model to a Poisson jump process during a period of the operation stage.

[20] That is, shippers are assumed to make their port choices before observing the realization of disaster occurrence or not. If the disaster occurs, shippers cannot make the decisions to switch ports. This assumption is based on that observations in Magala and Sommons (2008) and Tongzon (2009) that shippers/shipping lines often sign a long-term contract with terminal operators, and that *ad hoc* re-routing and rescheduling to other ports are difficult.

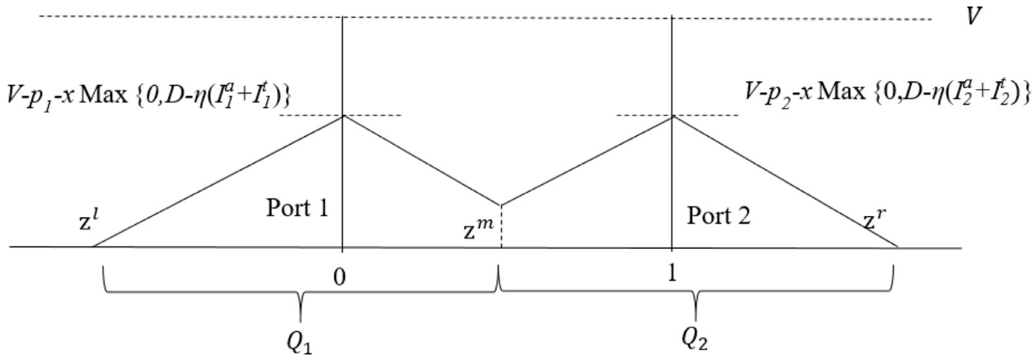

Fig. 3. Shipper's utility at each port after completion of adaptation investments.

Table 1
Notational glossary.

Parameter	Definition
V	Utility to shipper of using the port service
D	Disaster damage level to the shipper, and we assume $D < V$
η	Adaptation effectiveness to reduce damage
t	Unit distance transport cost for the shipper to move cargo to the port
I_i^a	Adaptation investment made by port authority at port i
I_i^t	Adaptation investment made by terminal operator at port i
x	Random variable denoting probability of the disaster occurrence
Ω	Expectation of x at the adaptation investment stage
Σ	Variance of x at the adaptation investment stage
Ψ	Second moment of x, which is equal to $\Omega^2+\Sigma$
p_i	Service fee charged by terminal operator to shippers at port i
φ_i	Concession fee charged by port authority to terminal operator port i
Q_i	Demand for service at port i at the operation stage
Π_i	Profit of terminal operator at port i at operation stage
π_i	Profit of port authority at port i at operation stage

ing to port adaptation investments. η measures the adaptation effectiveness to mitigate damage when disaster occurs. The disaster damage to shippers can include the cargo damage and inventory delay cost. If the disaster does not occur, shippers do not incur any cargo damage. With the disaster occurrence probability x, the expected damage incurred on shippers is $x\max\{0, D-\eta(I_i^a+I_i^t)\}$.[21]

Shippers are assumed to be uniformly distributed on the linear city with density 1, with each incurring a cost of t per unit distance to transport cargo from its location to the port. This transport cost can also capture any horizontal differentiation (service homogeneity) of two ports' services perceived by the shippers. Shippers choose which port to use, and directly pay the terminal operator. The terminal operator in turn pays the port authority a concession fee in exchange to use the port land and basic infrastructure. The port charging thus takes place in a vertical structure: the port authority chooses its concession fee φ_i on the terminal operator first, and then the terminal operator chooses service charge p_i on shippers. Table 1 summarizes the notations and parameters definitions in our model.

The shipper located in two ports' common hinterland (between point 0 and 1) can choose between the two ports for service. For a shipper located at a point z in the two ports' common hinterland, the utility of using port 1 is $V-p_1-zt-x\max\{0,\ D-\eta(I_1^a+I_1^t)\}$, and the utility of using port 2 is $V-p_2-(1-zt)-x\max\{0,\ D-\eta(I_2^a+I_2^t)\}$. The shippers located to the left of point 0 can only use port 1's service, and the line to the left of point 1 is defined as captive market for port 1. For a shipper located at a point z in port 1's captive hinterland, the utility is $V-p_1-|z|t-x\max\{0,\ D-\eta(I_1^a+I_1^t)\}$. Similarly, we assume the shippers located to the right of point 1 can only choose port 2's service, consisting port 2's captive market. For a shipper located at a point z in port 2's captive hinterland, the utility is $V-p_2-(z-1)t-x\max\{0,\ D-\eta(I_2^a+I_2^t)\}$. We can then derive the marginal shipper's location z^l, who is indifferent between using port 1's service and not using the port service at all; the marginal shipper's location z^m, who is indifferent between using port 1 and using port 2's service;

Shippers/shipping lines could commit to particular ports/terminals due to the integration and investment in hinterland transport, warehousing and other forms of cooperation with port sector (Chang et al., 2008; Wiegmans et al., 2008; Franc and van der Horst, 2010).

[21] Disaster damage D depends on the nature of the disasters faced by one particular port: for example, the damage to shippers from a hurricane, flooding or drought may be quite different. The disaster occurrence probability and damage can be affected by the port's geographic location and specific landscape. It is worth noting that our model is specified for a particular port region which is subject to one major disaster threat, and for a two-port region that is subject to the same disaster threat due to their locational proximity (i.e., the same values of damage D and disaster occurrence probability x).

and the marginal shipper's location z^r, who is indifferent between using port 2's service and not using the port services.

$$\left|z^l\right| = \frac{V - p_1 - x\max\left\{0,\ D - \eta\left(I_1^a + I_1^t\right)\right\}}{t} \tag{1.1}$$

$$z^r = 1 + \frac{V - p_2 - x\max\left\{0,\ D - \eta\left(I_2^a + I_2^t\right)\right\}}{t} \tag{1.2}$$

$$z^m = \frac{1}{2} + \frac{p_2 - p_1 - x\max\left\{0,\ D - \eta\left(I_1^a + I_1^t\right)\right\} + x\max\left\{0,\ D - \eta\left(I_2^a + I_2^t\right)\right\}}{2t} \tag{1.3}$$

The demand for each port at the operation stage is as follows, with $Q_1(p) = |z^l| + z^m$ and $Q_2(p) = (1 - z^m) + (z^r - 1)$:

$$Q_i(p) = \frac{1}{2} + \frac{2V + p_j - 3p_i + x\max\left\{0, D - \eta\left(I_j^a + I_j^t\right)\right\} - 3x\ \mathrm{Max}\left\{0, D - \eta\left(I_i^a + I_i^t\right)\right\}}{2t} \tag{2}$$

At the operation stage, the terminal operators' profits are $\Pi_i = (p_i - \varphi_i)Q_i$ and the port authorities' profits are $\pi_i = \varphi_i Q_i$. For the model tractability, we normalize the unit operating costs of port authorities and terminal operators to be zero.

At the adaptation investment stage, the terminal operators' expected profits are $E[\Pi_i] = [\int^{\Pi_i} f(x)dx] - 0.5\omega I_i^{t2}$, and the port authorities' expected profits are $E[\pi_i] = [\int^{\pi_i} f(x)dx] - 0.5\omega I_i^{a2}$. It is noted, at this stage, the port authorities incur the adaptation investment costs as $0.5\omega I_i^{a2}$, and the terminal operators incur cost as $0.5\omega I_i^{t2}$. The adaptation investment costs for both the port authorities and terminal operators are assumed to be in quadratic form, indicating an increasing marginal cost of adaptation as the technology requirement is higher, and the overall difficulty increases, to add more adaptation. Furthermore, ω is the adaptation cost parameter. Here, for model tractability and to focus on our main insights, we simply assume the port authorities and terminal operators to have the same adaptation investment cost structure, i.e., the same cost parameter ω. The shippers' surplus at the operation stage can be written as (CS for consumer surplus):

$$\begin{aligned} CS = &\int_0^{|z^l|} \left[V - p_1 - x\max\left\{0, D - \eta\left(I_1^a + I_1^t\right)\right\} - z\,t\right]dz + \int_0^{z^m} \left[V - p_1 - x\max\left\{0,\ D - \eta\left(I_1^a + I_1^t\right)\right\} - z\,t\right]dz \\ &+ \int_{z^m}^1 \left[V - p_2 - x\max\left\{0,\ D - \eta\left(I_2^a + I_2^t\right)\right\} - (1 - z)\,t\right]dz + \int_1^{z^r} \left[V - p_2 - x\max\left\{0,\ D - \eta\ \left(I_2^a + I_2^t\right)\right\}\right. \\ &\left. - (z - 1)t\right]dz \end{aligned} \tag{3}$$

The social welfare for the two-port system at the operation stage is $SW = CS + \sum_{i=1}^2 \pi_i + \sum_{i=1}^2 \Pi_i$.

We adopt backward induction to solve the model (subgame perfect Nash equilibrium). First, the operation stage is analyzed on the shipper port choice decision, and the pricing behavior of port authorities and terminal operators (Section 3.1). At the operation stage, port adaptation is completed and disaster occurrence probability x is realized. Second, we analyze port adaptation decisions at the investment stage, where disaster occurrence probability x is ambiguous with a Knightian uncertainty (Section 3.2).

3. Analysis

3.1. Port pricing

At the port operation stage, port adaptations I^a, I^t have been completed, and disaster occurrence probability x is also realized as a given value (no longer a distribution). For given concession fees φ_i by port authorities, the terminal operators set service charge p_i to be paid by shippers to maximize profits: $\max_{p_i} \Pi_i = (p_i - \phi_i)Q_i$. Solving the FOCs, $\frac{\partial \pi_i}{\partial p_i} = 0$ and $\frac{\partial \pi_j}{\partial p_j} = 0$, the equilibrium service charge can be obtained as follows (the expressions of FOCs, $\frac{\partial \pi_i}{\partial p_i} = 0$ and $\frac{\partial \pi_j}{\partial p_j} = 0$, are shown in Appendix A):[22]

$$p_i\left(\phi_i,\ \phi_j\right) = 0.2\left[(2V + t) + 2.57\phi_i + 0.42\phi_j - 2.43x\max\left\{0, D - \eta\left(I_i^a + I_i^t\right)\right\} + 0.42\mathrm{Max}\left\{0,\ D - \eta\left(I_j^a + I_j^t\right)\right\}\right] \tag{4}$$

where the second-order conditions (SOCs), $\frac{\partial^2 \pi_i}{\partial {p_i}^2} < 0$ and $\frac{\partial^2 \pi_j}{\partial {p_j}^2} < 0$, are also satisfied (Appendix A). It is noted that $p_i(\varphi_i, \varphi_j)$ is a function of two port authorities' concession fees φ_i and φ_j due to the interaction of two ports in their common hinterland market. As expected, φ_i has a greater impact on its own port charge $p_i(\varphi_i, \varphi_j)$ than on its rival port. Whilst the terminal operators at two ports compete, their port authorities may compete or cooperate. Pricing rules of the port authorities thus depend on inter-competition or cooperation (i.e., a monopoly in the latter case) which will be analyzed below separately.

[22] For infinite decimals in all the formulas, only two digits after the decimal points are reported in the paper to save space.

3.1.1. Pricing of competing port authorities

The problem of each competing port authority is: $\underset{\phi_i}{\text{Max}}\ \pi_i = \phi_i Q_i(p_i(\phi_i,\ \phi_j),\ p_j(\phi_i,\ \phi_j))$. Substituting $p_i(\varphi_i, \varphi_j)$ and $p_j(\varphi_i, \varphi_j)$ of Eq. (4) into π_i transforms the problem to: $\underset{\phi_i}{\text{Max}}\ \pi_i = \phi_i Q_i(\phi_i,\ \phi_j)$. Solving the resulting FOCs, $\frac{\partial \pi_i}{\partial \phi_i} = 0$ and $\frac{\partial \pi_j}{\partial \phi_j} = 0$, the equilibrium concession fee φ_i is as follows (the SOCs, $\frac{\partial^2 \pi_i}{\partial {\phi_i}^2} < 0$ and $\frac{\partial^2 \pi_j}{\partial {\phi_j}^2} < 0$, are satisfied) (the proofs are in Appendix A):

$$\bar{\phi}_i = 0.23(2V+t) - x\left[0.50 \max\left\{0,\ D - \eta\left(I_i^a + I_i^t\right)\right\} - 0.0445 \max\left\{0,\ D - \eta\left(I_j^a + I_j^t\right)\right\}\right] \tag{5.1}$$

Inserting $\bar{\phi}_1$ and $\bar{\phi}_2$ into $p_1(\varphi)$ and $p_2(\varphi)$, and $Q_1(p)$ and $Q_2(p)$ we have,

$$\bar{p}_i = 0.34(2V+t) - x\left[0.74 \max\left\{0,\ D - \eta\left(I_i^a + I_i^t\right)\right\} - 0.066 \max\left\{0,\ D - \eta\left(I_j^a + I_j^t\right)\right\}\right] \tag{5.2}$$

and

$$\bar{Q}_i = \frac{0.16\ (2V+t) - x\left[0.36 \max\left\{0,\ D - \eta\left(I_i^a + I_i^t\right)\right\} - 0.032 \max\left\{0,\ D - \eta\left(I_j^a + I_j^t\right)\right\}\right]}{t} \tag{5.3}$$

The following comparative statics are obtained to show the impact of adaptation investments on port charges and port demands. As can be seen, the port authority and terminal operator charge more (less), and have more (less) demand, if its own port (the other port) makes more adaptation investment (the detailed proofs are in Appendix A):

$$\frac{\partial \bar{\phi}_i}{\partial I_i^a} \geq 0;\ \frac{\partial \bar{\phi}_i}{\partial I_i^t} \geq 0;\ \frac{\partial \bar{\phi}_i}{\partial I_j^a} \leq 0;\ \frac{\partial \bar{\phi}_i}{\partial I_j^t} \leq 0$$
$$\frac{\partial \bar{p}_i}{\partial I_i^a} \geq 0;\ \frac{\partial \bar{p}_i}{\partial I_i^t} \geq 0;\ \frac{\partial \bar{p}_i}{\partial I_j^a} \leq 0;\ \frac{\partial \bar{p}_i}{\partial I_j^t} \leq 0$$

3.1.2. Pricing of a monopoly port authority

The monopoly port authority maximizes a joint profit of the two ports: $\underset{\phi_i,\phi_j}{\max} \sum_{i=1}^{2} \pi_i = \sum_{i=1}^{2} \phi_i Q_i(p_i(\phi_i,\ \phi_j),\ p_j(\phi_i,\ \phi_j))$. The FOCs are $\frac{\partial(\pi_i+\pi_j)}{\partial \phi_i} = 0$ and $\frac{\partial(\pi_i+\pi_j)}{\partial \phi_j} = 0$ (the SOCs $\frac{\partial^2(\pi_i+\pi_j)}{\partial {\phi_i}^2} < 0$ and $\frac{\partial^2(\pi_i+\pi_j)}{\partial {\phi_j}^2} < 0$, are satisfied). The equilibrium concession fees are $\tilde{\phi}_i = 0.25(2V+t) - 0.5x(\max\{0,\ D - \eta(I_i^a + I_i^t)\})$. Substituting $\tilde{\phi}_i$ into $p_i(\varphi_i,\varphi_j)$ and $Q_i(\varphi_i,\ \varphi_j)$ results in:

$$\tilde{p}_i = 0.35(2V+t) - x\left[0.74 \max\left\{0,\ D - \eta\left(I_i^a + I_i^t\right)\right\} - 0.043 \max\left\{0,\ D - \eta\left(I_j^a + I_j^t\right)\right\}\right] \tag{6.1}$$

and

$$\tilde{Q}_i = \frac{0.15\ (2V+t) - x\left[0.36 \max\left\{0,\ D - \eta\left(I_i^a + I_i^t\right)\right\} - 0.064 \max\left\{0,\ D - \eta\left(I_j^a + I_j^t\right)\right\}\right]}{t} \tag{6.2}$$

Below are the comparative statics of port charges and demands with respect to the adaptation investments. It can be seen that a monopoly port authority increases concession fee at one port when this port increases adaptation investment: i.e., $\frac{\partial \tilde{\phi}_i}{\partial I_i^a} \geq 0$; $\frac{\partial \tilde{\phi}_i}{\partial I_i^t} \geq 0$. In addition, with monopoly power, the port authority can raise concession fee when disaster is more likely to occur: i.e., $\frac{\partial \tilde{\phi}_i}{\partial x} \geq 0$. For a terminal operator, it can charge more when its port adapts more: i.e., $\frac{\partial \tilde{p}_i}{\partial I_i^a} \geq 0$; $\frac{\partial \tilde{p}_i}{\partial I_i^t} \geq 0$; but it charges less when the other port has more adaptation: i.e., $\frac{\partial \tilde{p}_i}{\partial I_j^a} \leq 0$; $\frac{\partial \tilde{p}_i}{\partial I_j^t} \leq 0$ (the proofs are in Appendix A):

$$\frac{\partial \tilde{\phi}_i}{\partial I_i^a} \geq 0;\ \frac{\partial \tilde{\phi}_i}{\partial I_i^t} \geq 0;\ \frac{\partial \tilde{\phi}_i}{\partial I_j^a} = 0;\ \frac{\partial \tilde{\phi}_i}{\partial I_j^t} = 0$$
$$\frac{\partial \tilde{p}_i}{\partial I_i^a} \geq 0;\ \frac{\partial \tilde{p}_i}{\partial I_i^t} \geq 0;\ \frac{\partial \tilde{p}_i}{\partial I_j^a} \leq 0;\ \frac{\partial \tilde{p}_i}{\partial I_j^t} \leq 0$$
$$\frac{\partial \tilde{Q}_i}{\partial I_i^a} \geq 0;\ \frac{\partial \tilde{Q}_i}{\partial I_i^t} \geq 0;\ \frac{\partial \tilde{Q}_i}{\partial I_j^a} \leq 0;\ \frac{\partial \tilde{Q}_i}{\partial I_j^t} \leq 0$$

Furthermore, we have $\bar{\phi}_i < \tilde{\phi}_i$ and $\bar{p}_i < \tilde{p}_i$ as shown below, which leads to our Lemma 1.

$$\tilde{\phi}_i - \bar{\phi}_i = 0.024\ \times (2V+t) - x\left[0.0039\text{Max}\left\{0,\ D - \eta\left(I_i^a + I_i^t\right)\right\} + 0.044\text{Max}\left\{0, D - \eta\left(I_j^a + I_j^t\right)\right\}\right] > 0$$

$$\tilde{p}_i - \bar{p}_i = 0.015\ \times (2V+t) - x\left[0.0058\text{Max}\left\{0,\ D - \eta\left(I_i^a + I_i^t\right)\right\} + 0.023\text{Max}\left\{0, D - \eta\left(I_j^a + I_j^t\right)\right\}\right] > 0$$

Lemma 1. *Conditional on the adaptation investments of two ports and the disaster occurrence probability, inter-port competition between the port authorities leads to lower concession fees and lower terminal operator charges.*

The results in Lemma 1 are expected. Lemma 2 summarizes the above comparative statics on the impacts of port adaptation on port charges:

Lemma 2. *For ports with competing port authorities, the concession fee and terminal operator charge increase with own port's adaptation, but decrease with the other port's adaptation. For a monopoly port authority, the concession fee and terminal operator charge also increase with own port's adaptation, but they are not affected by the other port's adaptation.*

As shown in Fig. A1 in Appendix A, for competing port authorities, when one port increases adaptation (e.g., port i), the "best response function" (BRF) of port j's concession fee $\varphi_j(\varphi_i)$ moves outward due to the stronger competing pressure from port i. The BRF of port i's concession fee $\varphi_i(\varphi_j)$ moves downward. Thus, at the new equilibrium, the concession fee rises at the port with an increased adaptation (port i), while the concession fee at the other port (port j) decreases. When one port increases adaptation, its terminal operator thus has to pay a higher concession fee and also has a higher shipper demand, both imposing positive effects on the terminal operator charge. When the other port increases adaptation, the terminal operator in question faces lower concession fee and also lower shipper demand, thus making it to reduce charge to shippers.

For a monopoly port authority, when adaptation at one port increases, the port authority raises concession fee. Meanwhile, it can internalize the positive externality of concession fee rise on the other port by not reducing the other port's concession fee. For terminal operator, the impact of adaptation change on its charge is the same. When one port increases adaptation, its terminal operator pays a higher concession fee while also having a larger shipper demand, both having positive effects on its charge. When the other port increases adaptation, the terminal operator in question pays a lower concession fee with lower shipper demand, making it to reduce charge to shippers.

Taking the derivatives of the differences in concession fees and terminal operator charges with respect to adaptation investments, we can see $\frac{\partial(\tilde{\phi}_i|(x,I^a,I^t)-\bar{\phi}_i|(x,I^a,I^t))}{\partial I} > 0$; $\frac{\partial(\tilde{p}_i|(x,I^a,I^t)-\bar{p}_i|(x,I^a,I^t))}{\partial I} > 0$, where $I \in \{I_i^a, I_i^t, I_j^a, I_j^t\}$. These results lead to our Proposition 1 as below.

Proposition 1. *Increased port adaptation at either port would enlarge the differences in both concession fee and terminal operator charge between the competing and cooperative ports.*

The intuition of Proposition 1 is as follows. With adaptation increased at one port, the monopoly port authority (the cooperative case) internalizes the externality to the other port, thus making the concession fee to rise more than that with the competing port authorities. The terminal operator charge increases with concession fee, such that its charge increases under a monopoly port authority. Therefore, the differences in both the concession fee and terminal charge between the competing and cooperative (monopoly) port authorities is enlarged. On the other hand, when the other port increases adaptation, the monopoly port authority does not change the concession fee at one port, whereas the competing port authorities would reduce concession fee in response. Thus, the differences in both the concession fee and terminal charge at one port is also enlarged when the other port increases adaptation.

3.2. Adaptation investments

At the adaptation investment stage, disaster occurrence probability x is, as indicated earlier, subject to a Knightian uncertainty. Specifically, x is a random variable with a pdf $f(x)$, expectation Ω, variance Σ, and the second moment $\Psi = Ex^2 = \Omega^2 + \Sigma$. Similar to the operation-stage analyses, we will, in the following subsections, discuss different inter-and intra- port competition and cooperation regimes. The port authorities and terminal operations are assumed to simultaneously make adaptation investment decisions. It is noted that adaptation projects are lengthy, such that each party makes adaptation decision well in-advance, while only observing completed adaptations by the others after a long-period.

3.2.1. Adaptation of competing port authorities

The pricing rule follows that of two competing port authorities at the operation stage $\bar{\phi}_i$ and $\bar{p}_i$. The expected profits for port authorities at the investment stage are $E[\pi_i] = [\int^{\pi_i} f(x)dx] - 0.5\omega I_i^{a2}$, and the expected profits for the terminal operators are $E[\Pi_i] = [\int^{\Pi_i} f(x)dx] - 0.50\omega I_i^{t2}$. The port authorities and terminal operators maximize these expected profits respectively. The constraints, $\eta(I_i^a + I_i^t) \le D$, must be imposed since ports cannot adapt beyond the maximum disaster damage level D: $\max_{I_i^a} \mathrm{E}[\pi_i]$, st. $\eta(I_i^a + I_i^t) \le D$; $\max_{I_i^t} \mathrm{E}[\Pi_i]$, st. $\eta(I_i^a + I_i^t) \le D$.

To solve the above constrained optimization problem, we first assume the constraints are not binding at equilibrium, and then discuss conditions to reach such interior solutions. For port authorities, the FOCs with respect to I_i^a are as follows:

$$\frac{\partial E[\pi_i]}{\partial I_i^a} = 0.33\frac{\eta}{t}\,[(V + 0.50t)\Omega - D\Psi] - 0.032\,\frac{\eta^2}{t}\Psi\left(I_j^a + I_j^t\right) + 0.36\,\frac{\eta^2}{t}\Psi I_i^t + \left(0.36\,\frac{\eta^2}{t}\Psi - \omega\right)I_i^a = 0 \tag{7.1}$$

The SOCs require $\omega \ge 0.36\,\frac{\eta^2}{t}\Psi$. This is to guarantee that the port authorities' expected profits are concave in I_i^a. If $\omega < 0.36\,\frac{\eta^2}{t}\Psi$, the profit functions are convex in I_i^a such that the marginal return of adaptation investment always increases,

implying the authorities keep investing till reaching $\eta(I_i^a + I_i^t) = D$, which is a "full insurance". The FOCs for the terminal operators are as follows:

$$\frac{\partial E[\Pi_i]}{\partial I_i^t} = 0.16\frac{\eta}{t}\left[(V + 0.50t)\Omega - D\Psi\right] - 0.015\,\frac{\eta^2}{t}\Psi\left(I_j^a + I_j^t\right) + 0.17\,\frac{\eta^2}{t}\Psi I_i^a + \left(0.17\,\frac{\eta^2}{t}\Psi - \omega\right)I_i^t = 0 \tag{7.2}$$

The SOCs require $\omega \geq 0.17\,\frac{\eta^2}{t}\Psi$ so that the terminal operators' expected profit functions are concave in I_i^t. If $\omega < 0.17\,\frac{\eta^2}{t}\Psi$, the marginal return of adaptation investment for terminal operators always increases, implying continuing investment till reaching $\eta(I_i^a + I_i^t) = D$.

The second derivatives indicate $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} \geq 0$; $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a} \leq 0$; $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t} \leq 0$, and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_i^t} \geq 0$; $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_j^a} \leq 0$; $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_j^t} \leq 0$. Consequently, adaptation investments of the port authority and terminal operator of the same port are strategic complements, while adaptation investments across the ports are strategic substitutes. In Appendix B, we plot the BRFs of adaptation I_i^a and I_i^t at the same port, and I_i^a and I_j^a at two different ports. The BRFs of I_i^a and I_i^t are positively sloped while those of I_i^a and I_j^a are negatively sloped.

Solving the system equations of the FOCs, and imposing symmetry, we obtain the following symmetric interior equilibrium adaptation investments with the competing port authorities:

$$\bar{I}_i^a = \frac{\eta\left[(2V + t)\,\Omega - 2D\Psi\right]}{6.1\,\omega t - 3\Psi\eta^2} \geq \bar{I}_i^t = \frac{\eta\left[(2V + t)\,\Omega - 2D\Psi\right]}{2.1\left(6.1\,\omega t - 3\,\Psi\eta^2\right)}$$

The condition of finite level of adaptation investments implies $\omega > 0.49\frac{\eta^2}{t}\Psi$ (the denominator of $\bar{I}_i^a$ and $\bar{I}_i^t$ to be positive and non-zero), whereas the existence of interior solution requires $\omega \geq \frac{0.48\,\Omega(V+0.50t)\eta^2}{Dt}$. It is noted that when constraint $\eta(I_i^a + I_i^t) \leq D$ is binding at equilibrium, i.e., $\eta(I_i^a + I_i^t) = D$, there would be an infinite number of Nash equilibria of adaptation investments (see Appendix B for discussion). This happens when $\omega \leq \frac{0.48\,\Omega(V+0.50t)\eta^2}{Dt}$ such that adaptation is not costly enough, such that the ports adapt as much as possible to achieve a full insurance. This case of infinite Nash equilibria with binding constraint makes comparison between $\bar{I}_i^a$ and $\bar{I}_i^t$ and other implications of Knightian uncertainty unclear. In addition, in practise, port adaptation is likely to be extremely costly (OECD, 2016) and as a result, ports seldom fully adapt to a potential disaster (see the survey in Becker et al., 2012). Therefore, to simplify our discussion and to reflect the real practice, we exclude discussion on the multiple equilibria under binding constraints. Taking total derivatives of the FOCs ($\frac{\partial E[\pi_i]}{\partial I_i^a} = 0$ and $\frac{\partial E[\Pi_i]}{\partial I_i^t} = 0$) with respect to Ω and Σ respectively, and imposing the symmetry assumption, the expressions of $\frac{\partial \bar{I}_i^a}{\partial \Omega}$, $\frac{\partial \bar{I}_i^t}{\partial \Omega}$ and $\frac{\partial \bar{I}_i^a}{\partial \Sigma}$, $\frac{\partial \bar{I}_i^t}{\partial \Sigma}$ can be derived as shown in Appendix C, with the following signs observed:

$$\frac{\partial \bar{I}_i^a}{\partial \Omega} \geq 0,\ \frac{\partial \bar{I}_i^t}{\partial \Omega} \geq 0,\ \frac{\partial \bar{I}_i^a}{\partial \Sigma} \leq 0 \text{ and } \frac{\partial \bar{I}_i^t}{\partial \Sigma} \leq 0$$

As can be seen in Appendix C, the signs of $\frac{\partial \bar{I}_i^a}{\partial \Omega}$ and $\frac{\partial \bar{I}_i^t}{\partial \Omega}$ are determined by the terms $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}$. As a higher expectation of disaster occurrence probability increases the marginal expected profits of the port authority and terminal operator with respect to their own adaptation, i.e., $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} \geq 0$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} \geq 0$, the equilibrium port adaptations also increase with the expectation of disaster occurrence probability, i.e., $\frac{\partial \bar{I}_i^a}{\partial \Omega} \geq 0$ and $\frac{\partial \bar{I}_i^t}{\partial \Omega} \geq 0$.

Furthermore, the signs of $\frac{\partial \bar{I}_i^a}{\partial \Sigma}$ and $\frac{\partial \bar{I}_i^t}{\partial \Sigma}$ are determined by $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}$. As a larger variance of disaster occurrence probability decreases the marginal expected profits of the port authority and terminal operator with respect to their own adaptation, the equilibrium port adaptations decrease with the variance of disaster occurrence probability, i.e., $\frac{\partial \bar{I}_i^a}{\partial \Sigma} \leq 0$ and $\frac{\partial \bar{I}_i^t}{\partial \Sigma} \leq 0$.

3.2.2. Adaptation of a monopoly port authority

The pricing rule at the operation stage follows that of a monopoly authority regime analyzed in Section 3.1, i.e., $\tilde{\phi}_i$ and $\tilde{p}_i$. For a monopoly port authority, the expected joint profit is $E[\pi_i + \pi_j] = [\int(\pi_i + \pi_j)f(x)dx] - 0.50\omega({I_i^a}^2 + {I_j^a}^2)$. The authority maximizes the expected joint profit by choosing adaptation at two ports jointly: $\max_{I_i^a,\, I_j^a} E[\pi_i + \pi_j]$, st. $\eta(I_i^a + I_i^t) \leq D$ and $\eta(I_j^a + I_j^t) \leq D$. The FOCs are as follows:

$$\frac{\partial E\left[\pi_i + \pi_j\right]}{\partial I_i^a} = 0.30\frac{\eta}{t}\left[(V + 0.50t)\Omega - D\Psi\right] - 0.064\,\frac{\eta^2}{t}\Psi\left(I_j^a + I_j^t\right) + 0.36\,\frac{\eta^2}{t}\Psi I_i^t + \left(0.36\,\frac{\eta^2}{t}\Psi - \omega\right)I_i^a = 0 \tag{8.1}$$

where the SOCs require that $\omega \geq 0.36\,\frac{\eta^2}{t}\Psi$. The terminal operators maximize their expected profit as $\max\limits_{I_i^t} \mathrm{E}[\Pi_i]$; s.t. $\eta\,(I_i^a + I_i^t) \leq D$, with the FOCs as,

$$\frac{\partial\, E[\Pi_i]}{\partial I_i^t} = 0.15\frac{\eta}{t}\,[(V+0.5t)\Omega - D\Psi] - 0.031\,\frac{\eta^2}{t}\Psi\left(I_j^a + I_j^t\right) + 0.18\,\frac{\eta^2}{t}\Psi I_i^a - \left(\omega - 0.18\,\frac{\eta^2}{t}\Psi\right)I_i^t = 0 \tag{8.2}$$

and the SOCs $\omega \geq 0.18\,\frac{\eta^2}{t}\Psi$. The second derivatives show $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_i^t} \geq 0$; $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^a} \leq 0$; $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^t} \leq 0$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_i^t} \geq 0$; $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_j^a} \leq 0$; $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_j^t} \leq 0$. The adaptations of the port authority and terminal operator within the same port are thus strategic complements, while the adaptations across the ports are strategic substitutes.

Solving the system equations of the FOCs for symmetric interior Nash equilibrium, we obtain the following solutions and relationship:

$$\tilde{I}_i^a = \frac{\eta[(2V+t)\,\Omega - 2D\Psi]}{6.70\omega t - 3\Psi\eta^2} \geq \tilde{I}_i^t = \frac{\eta[(2V+t)\Omega - 2D\Psi]}{14\omega t - 6\Psi\eta^2}$$

The condition of finite level of adaptation investments requires $\omega > 0.45\,\frac{\eta^2}{t}\Psi$, while the interior solution requires $\omega \geq \frac{0.22\,\Omega(V+0.5t)\eta^2}{Dt}$. Taking total derivative of the FOCs ($\frac{\partial E[\pi_i+\pi_j]}{\partial I_i^a} = 0$ and $\frac{\partial\, E[\Pi_i]}{\partial I_i^t} = 0$) with respect to Ω and Σ respectively, and imposing the symmetry assumption, $\frac{\partial \tilde{I}_i^a}{\partial\Omega}$, $\frac{\partial\, \tilde{I}_i^t}{\partial\Omega}$ and $\frac{\partial \tilde{I}_i^a}{\partial\Sigma}$, $\frac{\partial\, \tilde{I}_i^t}{\partial\Sigma}$ can be derived, with the following signs:

$$\frac{\partial \tilde{I}_i^a}{\partial\Omega} \geq 0,\ \frac{\partial\, \tilde{I}_i^t}{\partial\Omega} \geq 0,\ \frac{\partial \tilde{I}_i^a}{\partial\Sigma} \leq 0 \text{ and } \frac{\partial\, \tilde{I}_i^t}{\partial\Sigma} \leq 0$$

The expressions and proofs of the above comparative statics are also collated in Appendix C. Like the case of the competing port authorities, we find that the signs of $\frac{\partial \tilde{I}_i^a}{\partial\Omega}$ and $\frac{\partial\, \tilde{I}_i^t}{\partial\Omega}$ depend on $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial\Omega}$, $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial\Omega}$. $\frac{\partial \tilde{I}_i^a}{\partial\Omega} \geq 0$ and $\frac{\partial\, \tilde{I}_i^t}{\partial\Omega} \geq 0$, as $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial\Omega} \geq 0$ and $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial\Omega} \geq 0$. That is, as a higher expectation of disaster occurrence probability increases the marginal expected profits of terminal operators, as well as the marginal joint expected profit of the monopoly port authority, with respect to own adaptation, the equilibrium adaptations increase as a result. The signs of $\frac{\partial \tilde{I}_i^a}{\partial\Sigma}$, $\frac{\partial\, \tilde{I}_i^t}{\partial\Sigma}$ depend on $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial\Sigma}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial\Sigma}$, and we have $\frac{\partial \tilde{I}_i^a}{\partial\Sigma} \leq 0$ and $\frac{\partial\, \tilde{I}_i^t}{\partial\Sigma} \leq 0$ since $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial\Sigma} \leq 0$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial\Sigma} \leq 0$. That is, as larger variance of disaster occurrence probability reduces the marginal expected profit of the monopoly port authority and terminal operators with respect to own adaptation, the equilibrium port adaptations decrease as a result.

3.2.3. Adaptation of competing port authorities with intra-port coordination

Under this regime, the port authorities compete with each other, but each coordinates with its terminal operators on adaptation decision. The pricing rule at the operation stage follows that of the competing port authorities, i.e. $\bar{\phi}_i$ and $\bar{p}_i$. The port authority and terminal operator at the same port now jointly maximize profit: $\max\limits_{I_i^a, I_i^t} E[\pi_i + \Pi_i]$, s.t. $\eta(I_i^a + I_i^t) \leq D$. The FOCs for this intra-port coordination problem are as follows:

$$\frac{\partial E[\pi_i + \Pi_i]}{\partial I_i^a} = \frac{\partial E[\pi_i + \Pi_i]}{\partial I_i^t} = 0.48\frac{\eta}{t}\,[(V+0.50t)\Omega - D\Psi] - 0.048\,\frac{\eta^2}{t}\Psi\left(I_j^a + I_j^t\right) + 0.53\,\frac{\eta^2}{t}\Psi\, I_i^t$$
$$+\left(0.53\,\frac{\eta^2}{t}\Psi - \omega\right)I_i^a = 0 \tag{9.1}$$

and the SOCs require $\omega \geq 0.53\frac{\eta^2}{t}\Psi$. The second derivatives show $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} \geq 0$; $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a} \leq 0$; $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t} \leq 0$. The adaptation investments of the port authority and terminal operator at the same port are strategic complements, while the investments across the ports are strategic substitutes. Solving the system equations of the FOCs, the symmetric interior Nash equilibrium is obtained as follows:

$$\hat{I}_i^a = \hat{I}_i^t = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{4.1\,\omega t - 4\,\Psi\eta^2}$$

The condition of finite level of the adaptation investments requires $\omega > 0.98\,\frac{\eta^2}{t}\Psi$. The interior Nash equilibrium requires $\omega \geq \frac{0.97\,\Omega(V+0.5t)\eta^2}{Dt}$. Furthermore, taking total derivative of the FOCs ($\frac{\partial E[\pi_i+\Pi_i]}{\partial I_i^a} = 0$ and $\frac{\partial E[\pi_i+\Pi_i]}{\partial I_i^t} = 0$) with respect to Ω and Σ respectively, and imposing the symmetry assumption, we have:

$$\frac{\partial \hat{I}_i^a}{\partial\Omega} \geq 0,\ \frac{\partial \hat{I}_i^t}{\partial\Omega} \geq 0,\ \frac{\partial \hat{I}_i^a}{\partial\Sigma} \leq 0 \text{ and } \frac{\partial \hat{I}_i^t}{\partial\Sigma} \leq 0$$

Table 2
The summary of the equilibrium port adaptations with private port authorities.

Regimes	Port authority adaptation	Terminal operator adaptation	SOCs and finite level of adaptation	Interior solution requirement
Competing Port Authorities	$\bar{I}_i^a = \frac{\eta\,[(2V+t)\,\Omega-2D\Psi]}{6.1\omega t-3\Psi\eta^2}$	$\bar{I}_i^t = \frac{\eta\,[(2V+t)\,\Omega-2D\Psi]}{2.1\,(6.1\,\omega t-3\,\Psi\eta^2)}$	$\omega > 0.49\,\frac{\eta^2}{t}\,\Psi$	$\omega \geq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$
Monopoly Port Authority	$\tilde{I}_i^a = \frac{\eta\,[(2V+t)\,\Omega-2D\Psi]}{6.7\omega t-3\,\Psi\eta^2}$	$\tilde{I}_i^t = \frac{\eta\,[(2V+t)\,\Omega-2D\Psi]}{13.7\,\omega t-6.1\,\Psi\eta^2}$	$\omega > 0.45\,\frac{\eta^2}{t}\,\Psi$	$\omega \geq \frac{044\,\Omega(V+0.5t)\eta^2}{Dt}$
Competing Port Authorities with Intra-port Coordination	$\hat{I}_i^a = \frac{\eta\,[(2V+t)\,\Omega-2D\Psi]}{4.1\omega t-4\,\Psi\eta^2}$	$\hat{I}_i^t = \frac{\eta\,[(2V+t)\,\Omega-2D\Psi]}{4.1\omega t-4\,\Psi\eta^2}$	$\omega > 0.98\,\frac{\eta^2}{t}\,\Psi$	$\omega \geq \frac{0.97\,\Omega(V+0.5t)\eta^2}{Dt}$

The expressions and derivation of the above comparative statics are given in Appendix C as well, from which we can see the signs of $\frac{\partial \hat{I}_i^a}{\partial \Omega}$ and $\frac{\partial \hat{I}_i^t}{\partial \Omega}$ depend on $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega}$, $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Omega}$. $\frac{\partial \hat{I}_i^a}{\partial \Omega} \geq 0$ and $\frac{\partial \hat{I}_i^t}{\partial \Omega} \geq 0$, as $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega} \geq 0$ and $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Omega} \geq 0$. That is, as a higher expectation of disaster occurrence probability increases the marginal joint profit of the port authority and terminal operator with respect to their own adaptation, the equilibrium adaptation thus increases. In a similar fashion, the signs of $\frac{\partial \hat{I}_i^a}{\partial \Sigma}$, $\frac{\partial \hat{I}_i^t}{\partial \Sigma}$ depend on $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma}$, $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Sigma}$: $\frac{\partial \hat{I}_i^a}{\partial \Sigma} \leq 0$ and $\frac{\partial \hat{I}_i^t}{\partial \Sigma} \leq 0$, as $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma} \leq 0$ and $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Sigma} \leq 0$. That is, as a larger variance of disaster occurrence probability reduces the marginal joint profit of the port authority and terminal operator with respect to their own adaptation, the equilibrium port adaptation falls as a result.

Table 2 summarizes the interior equilibrium adaptations, the SOCs, finite level of adaptation and conditions of interior equilibrium adaptation for the three regimes discussed above. Proposition 2 follows from the preceding discussion:

Proposition 2. *A higher expectation of disaster occurrence probability increases port adaptation investments, while a larger variance of disaster occurrence probability reduces port adaptation investments.*

This analytical result concerning the impact of Knightian uncertainty on port adaptation provides an explanation for why in practice port adaptation appears much more difficult to implement than port mitigation, in that our present knowledge about climate change and related disasters is far from reasonable accuracy (a large variance of disaster occurrence probability). For example, Becker et al. (2012) and Ng et al. (2016) found that most of their surveyed ports cite the "inadequate information" and need to know more about the issue as a major reason for slow development of port adaptation plans. One specific example is the great uncertainty faced by Port of Vancouver in Canada, with the current prediction for Vancouver's SRL in 2100 having a very wide confidence interval (from 0.2 to 1.5 meters).[23] Furthermore, the relatively low probability of climate change-related disasters could also discourage port adaptation investment. This is exemplified by Gulfport's (Mississippi) decision to exclusively use the post-Katrina grant (US$570 million) allocated by the US federal government to expand capacity, while canceling terminal elevation project to help protect against another Katrina-like hurricane. Although not severely affected by Hurricanes Harvey and Irma in August 2017, this port has been alerted that disaster occurrence probability may not be as low as it once perceived. The increase in the expectation of disaster occurrence probability stimulates adaptation investment. Ng et al. (2016) found that the Canadian ports subject to higher climate change risk invest more adaptation. Proposition 2 is also consistent with existing economics and decision science literature. Camerer and Weber (1992) modeled a subjective expected utility (SEU) with Knightian uncertainty on event occurrence probability. They found people prefer to bet on events they know more about, even when their beliefs are held constant as people are averse to ambiguity about the probability. Nishimura and Ozaki (2007) investigated the effect of Knightian uncertainty on project investment decisions. It is found that ambiguity of Knightian uncertainty decreases the value of irreversible investment while the increase in risk increases it.

We can further show:

$$\hat{I}_i^a - \bar{I}_i^a = \frac{0.079\ \times \eta(2V\Omega - 2D\Psi + \Omega t)\left(\omega t + 0.51\Psi\eta^2\right)}{\left(\omega t - 0.97\Psi\eta^2\right)\left(\omega t - 0.48\Psi\eta^2\right)} > 0;\ \bar{I}_i^a - \tilde{I}_i^a = \frac{0.0132\ \times \eta(2V\Omega - 2D\Psi + \Omega t)\omega t}{\left(\omega t - 0.48\Psi\eta^2\right)\left(\omega t - 0.45\Psi\eta^2\right)} > 0$$

Analogously, one can show $\hat{I}_i^t \geq \bar{I}_i^t \geq \tilde{I}_i^t$, leading to the following Proposition 3.

Proposition 3. *Port authorities' competition leads to higher adaptation investments (the "competition effect"), whereas intra-port coordination between the port authority and terminal operator at each port also increases adaptation investments. Thus, without intra-port coordination, the port authority and terminal operator at a port "free ride" on each other's adaptation by investing in less in adaptation (the "free-riding effect").*

As shown earlier, the adaptation investments across the ports are strategic substitutes such that an increase in one port's adaptation imposes a negative effect on the other port's expected profit. When the two ports are controlled by a monopoly port authority, it coordinates to internalize such a negative effect through reducing adaptation investment at two ports (the competition effect). On the other hand, the adaptation investments by the port authority and terminal operator of the same

[23] The Globe and Mail Article on May 13, 2018, available at: https://www.theglobeandmail.com/canada/article-for-port-of-vancouver-underestimating-pacific-sea-level-rises-could/?utm_medium=Referrer:+Social+Network+/+Media&utm_campaign=Shared+Web+Article+Links.

are, as shown earlier, strategic complements. Coordination between the two entities would then stimulate total adaptation investments (the free-riding effect).

Furthermore, the ratio of the adaptation investments of the two regimes (the competing port authorities vs. a monopoly port authority) is $\frac{\bar{I}_i^a}{\tilde{I}_i^a} = 1.09 \times \frac{(\omega t - 0.45\Psi\eta^2)}{(\omega t - 0.49\Psi\eta^2)}$, which measures the degree of the competition effect. $\frac{\partial}{\partial\Omega}\left(\frac{\bar{I}_i^a}{\tilde{I}_i^a}\right) = \frac{0.085\ \Omega\eta^2\omega t}{(\omega t - 0.49\Psi\eta^2)^2} > 0$; $\frac{\partial}{\partial\Sigma}(\frac{\bar{I}_i^a}{\tilde{I}_i^a}) = \frac{0.042\ \Omega\eta^2\omega t}{(\omega t - 0.485\Psi\eta^2)^2} > 0$. Analogously, $\frac{\partial}{\partial\Omega}\left(\frac{\bar{I}_i^t}{\tilde{I}_i^t}\right) > 0$, $\frac{\partial}{\partial\Sigma}\left(\frac{\bar{I}_i^t}{\tilde{I}_i^t}\right) > 0$. The ratio of the adaptation investments between intra-port coordination and no coordination for the competing port authorities is $\frac{\hat{I}_i^a}{\bar{I}_i^a} = 1.49 \times \frac{(\omega t - 0.49\Psi\eta^2)}{(\omega t - 0.97\Psi\eta^2)}$, which measures the degree of the free-riding effect. $\frac{\partial}{\partial\Omega}\left(\frac{\hat{I}_i^a}{\bar{I}_i^a}\right) = \frac{1.44\ \Omega\eta^2\omega t}{(\omega t - 0.97\Psi\eta^2)^2} > 0$; $\frac{\partial}{\partial\Sigma}\left(\frac{\hat{I}_i^a}{\bar{I}_i^a}\right) = \frac{0.72\ \Omega\eta^2\omega t}{(\omega t - 0.97\Psi\eta^2)^2} > 0$. Analogously, it can be proved that $\frac{\partial}{\partial\Omega}\left(\frac{\hat{I}_i^t}{\bar{I}_i^t}\right) > 0$; $\frac{\partial}{\partial\Sigma}\left(\frac{\hat{I}_i^t}{\bar{I}_i^t}\right) > 0$. The discussion leads to the following Proposition 4.

Proposition 4. *Both a higher expectation and a larger variance of disaster occurrence probability strengthen the competition effect and the free-riding effect.*

Proposition 4 may be explained as follows: For the competition effect, when the two port authorities compete on adaptation investment, if the expectation of disaster occurrence probability rises, they have a stronger incentive to adapt as compared to a monopoly port authority, strengthening the competition effect. When the variance of disaster occurrence probability increases, the two ports reduce adaptation investment (Proposition 2). However, when the port authorities compete, they would reduce adaptation less as compared to a monopoly port authority. As a result, an increased variance of disaster occurrence probability also enlarges the difference in adaptation between the competing port authorities and monopoly port authority, enhancing the competition effect. For the free-riding effect, when the expectation of disaster occurrence probability rises, the marginal expected profit of adaptation investment is larger, such that one party (port authority or terminal operator) benefits more from the other party's adaptation, thus enhancing the free-riding incentive. When the variance of disaster occurrence probability increases, each party reduces adaptation. Without coordination, such reduction is more significant, thus also enlarging the difference with and without intra-port coordination. This strengthens the free-riding effect.

Last, we investigate the implications of inter-port competition and intra-port cooperation on social welfare of the two-port system. $E[\overline{SW}]$ is the expected welfare with the competing port authorities; $E[\widetilde{SW}]$ is the expected welfare with a monopoly port authority; $E[\widehat{SW}]$ is the expected welfare with the competing port authorities with intra-port coordination. The expression of $E[\widehat{SW}] - E[\overline{SW}]$ is shown as:

$$E[\widehat{SW}] - E[\overline{SW}] = \frac{0.048\omega(t^2\omega^2 - 0.96\Psi\eta^2 t\omega + 0.068\Psi^2\eta^2)\eta^2(2\Omega V - 2D\Psi + \Omega t)^2}{(\omega t - 0.49\Psi\eta^2)^2}(\omega t - 0.97\Psi\eta^2)^2 > 0$$

The sign of $E[\widehat{SW}]-E[\overline{SW}]$ is determined by the term, $t^2\omega^2 - 0.96\Psi\eta^2 t\omega + 0.068\Psi^2\eta^2$, in the numerator, which is a convex quadratic function of ω. The two solutions of $t^2\omega^2 - 0.96\Psi\eta^2 t\omega + 0.068\Psi^2\eta^2 = 0$ are $0.096\,\frac{\eta^2}{t}\Psi$ and $0.86\,\frac{\eta^2}{t}\Psi$. The condition of finite level of adaptation for $\hat{I}_i^a$ and $\hat{I}_i^t$ suggests $\omega \geq 0.98\frac{\eta^2}{t}\Psi$, such that $t^2\omega^2 - 0.96\Psi\eta^2 t\omega + 0.068\Psi^2\eta^2 > 0$. Thus $E[\widehat{SW}]-E[\overline{SW}] > 0$. The expression of $E[\overline{SW}] - E[\widetilde{SW}]$ is shown as:

$$E\left[\overline{SW}\right] - E\left[\widetilde{SW}\right] = \frac{0.0056\ \times \omega^2\eta^2 t(2\Omega V - 2D\Psi + \Omega t)^2\left(\omega t - 0.47\Psi\eta^2\right)}{\left(\omega t - 0.445\Psi\eta^2\right)^2\left(\omega t - 0.49\Psi\eta^2\right)^2} > 0$$

The ranking of expected welfare is thus $E[\widehat{SW}] > E[\overline{SW}] > E[\widetilde{SW}]$, leading to the following Proposition 5.

Proposition 5. *When port authorities are private, the expected welfare increases with port adaptation investments. Intra-port coordination between port authorities and terminal operators results in the highest expected welfare by overcoming the free-riding effect. A monopoly port authority, on the contrary, leads to the lowest port adaptation investment and expected welfare among the three regimes (namely, competing port authorities, a monopoly port authority, and competing port authorities with intra-port coordination).*

Proposition 5 has useful policy implications. First, from the welfare perspective, with an uncertain natural disaster threat, it may be better to have the ports controlled by different private port authorities. Inter-port competition between private port authorities results in more adaptation, and higher expected welfare. Second, intra-port coordination on adaptation between the port authority and terminal operator should be encouraged to mitigate the free-riding effect on adaptation. Here, the experience of San Diego port can be useful: as discussed in Becker et al. (2013), the port has developed framework and mechanism so as to involve terminal operators to discuss, plan and implement port adaptation projects.

4. Effects of port competition intensity

Ports' service differentiation can moderate inter-port competition (Wang et al., 2012), thus potentially affecting port adaptation investments. Ports with more homogenous services are likely to compete more fiercely. For example, Shenzhen and

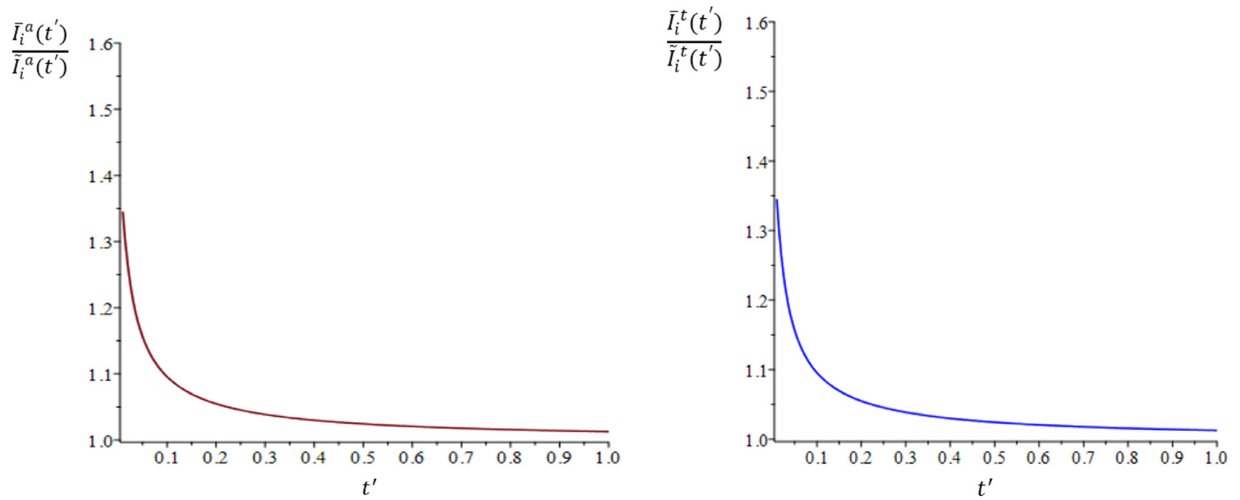

Fig. 4. Numerical values of $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$ with changing t' ($\Psi = 0.1$, $\eta = 2$, $\omega = 25$, $t = 0.1$). *Note:* Larger values of $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$ suggest a stronger "competition effect" on port adaptation.

Hong Kong ports both focus on their role as a container cargo gateway to South China, thus intensifying their competition. On the other hand, Rotterdam and Amsterdam ports compete less fiercely as they have different business focuses. In this section, we explicitly model such inter-port competition intensity by allowing the shippers in the common hinterland to have a different transport cost parameter as opposed to each port's captive catchment area. Specifically, we let the shipper in the common hinterland have a different transport cost, t', compared to the transport cost, t, for shippers in two ports' own captive catchments. The parameter t' thus helps capture port service heterogeneity in the hinterland market, and a smaller t' suggests a lower level of port service heterogeneity, equivalent to a more intense inter-port competition. With this new parameter t', the pricing rule at the operation stage can be solved first. Then, the new equilibrium adaptation investments with competing port authorities $(\bar{I}_i^a(t'), \bar{I}_i^t(t'))$, a monopoly port authority $(\tilde{I}_i^a(t'), \tilde{I}_i^t(t'))$ and competing port authorities with intra-port coordination $(\hat{I}_i^a(t'), \hat{I}_i^t(t'))$ can be obtained. The expressions of these equilibrium adaptations are long and thus collated in Appendix D.

The competition effect is measured by the ratios $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$. The comparative statics, $\frac{\partial}{\partial t'}(\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')})$ and $\frac{\partial}{\partial t'}(\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')})$, shed light on the impact of inter-port competition intensity (port service homogeneity) on the "competition effect" of port adaptation. However, $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$ are high order polynomial of t', such that the analytical result on comparative statics $\frac{\partial}{\partial t'}(\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')})$ and $\frac{\partial}{\partial t'}(\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')})$ is difficult to reach. Numerical simulation is conducted with the parameter values $\Psi = 0.1$, $\eta = 2$, $\omega = 25$, $t = 0.1$. Fig. 4 shows the numerical values of $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$ with changes in t'. When t' increases, the values of ratios $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$ decrease. That is, when the two ports become more competitive, or port services are more homogenous, the competition effect on port adaptation is strengthened. Robustness check was also done with a wide range of the different parameter values, and our conclusions keep consistent qualitatively.[24]

The free-riding effect is reflected by the ratios $\frac{\hat{I}_i^a(t')}{\bar{I}_i^a(t')}$ and $\frac{\hat{I}_i^t(t')}{\bar{I}_i^t(t')}$. The inter-port competition intensity (port service homogeneity) might also affect incentive of the port authority and terminal operator to free-ride on each other's adaptation within one port. Numerical simulation demonstrates the relation between values of $\frac{\hat{I}_i^a(t')}{\bar{I}_i^a(t')}$, $\frac{\hat{I}_i^t(t')}{\bar{I}_i^t(t')}$ and the parameter t' (Fig. 5). It is noted when t' increases, the values of ratios $\frac{\hat{I}_i^a(t')}{\bar{I}_i^a(t')}$, $\frac{\hat{I}_i^t(t')}{\bar{I}_i^t(t')}$ decrease as well. This suggests that more intense inter-port competition (more service homogeneity) can strengthen the free-riding effect on adaptation between port authority and terminal operator at the same port. This finding makes sense since when two ports compete more fiercely in the common hinterland market, one port's adaptation contributes more to gain competitive advantage in this competing market. Therefore, within one port, port authority and terminal operator have stronger incentive to free-ride on each other's adaptation. We summarize the impact of inter-port competition intensity (port service homogeneity) on the competition and free-riding effects in Proposition 6.

[24] The results of the robustness check with alternative parameter values are available upon request. They are not reported in the manuscript to save space.

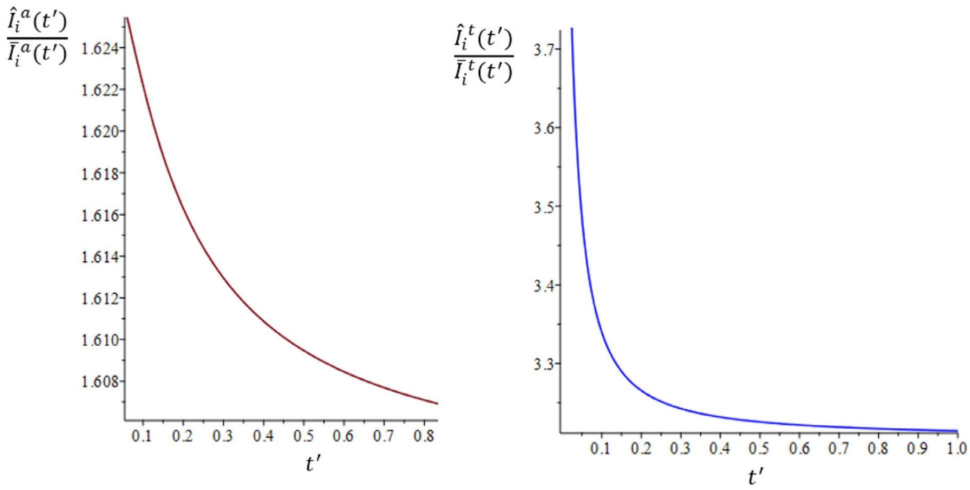

Fig. 5. Numerical values of $\frac{\hat{I}_i^a(t')}{\bar{I}_i^a(t')}$ and $\frac{\hat{I}_i^t(t')}{\bar{I}_i^t(t')}$ with changing t' ($\Psi = 0.1$, $\eta = 2$, $\omega = 25$, $t = 0.1$). *Note:* Larger values of $\frac{\hat{I}_i^a(t')}{\bar{I}_i^a(t')}$ and $\frac{\hat{I}_i^t(t')}{\bar{I}_i^t(t')}$ suggest a stronger "free-riding effect" on port adaptation.

Proposition 6. *More intense inter-port competition (less service heterogeneity) strengthens both the competition effect on adaptation between the two ports, and the free-riding effect on adaptation between port authority and terminal operator within one port.*

5. Public ownership of port authorities

In this section, we extend our discussion to consider public ownership of the two port authorities that aim to maximize social welfare (rather than profits as considered in the above analysis). Specifically, two public port authorities compete with each other, each maximizing the regional/local social welfare SW_i, including its own profit π_i, its terminal operator's profit Π_i and the surplus of shippers who use its port's service CS_i (i.e., $SW_i = \pi_i + \Pi_i + CS_i$). On the other hand, the monopoly public port authority maximizes total welfare of the two-port system, i.e., $SW = (\pi_1 + \pi_2) + (\Pi_1 + \Pi_2) + (CS_1 + CS_2)$. To distinguish with the case of private port authorities, we use $I^a_{(g)i}$ and $I^t_{(g)i}$ to stand for, respectively, adaptation investments under public port authorities, and $\varphi_{(g)i}$ and $p_{(g)i}$ to represent, respectively, the concession fee and terminal operator charge.[25]

5.1. Public port authorities' pricing

Conditional on port adaptations $I^a_{(g)i}$ and $I^t_{(g)i}$, the (private) terminal operators continue to maximize own profits, while the competing public port authorities maximize the regional welfare by choosing concession fee at the operation stage: $\max_{\phi_i} SW_i = \pi_i + \Pi_i + CS_i$. The equilibrium concession fee and terminal operator charge can be solved as:

$$\bar{\phi}_{(g)i} = -(1.361V - 0.014t) + x\left[1.36 \max\left\{0,\ D - \eta\left(I^a_{(g)i} + I^t_{(g)i}\right)\right\} + \max\left\{0,\ D - \eta\left(I^a_{(g)j} + I^t_{(g)j}\right)\right\}\right] \tag{10.1}$$

$$\bar{p}_{(g)i} = -0.208(2V - t) + 0.208x\left[\max\left\{0,\ D - \eta\left(I^a_{(g)i} + I^t_{(g)i}\right)\right\} + \max\left\{0,\ D - \eta\left(I^a_{(g)j} + I^t_{(g)j}\right)\right\}\right] \tag{10.2}$$

The monopoly public port authority maximizes welfare by choosing the concession fees at both ports at the operation stage: $\max_{\phi_1,\phi_2} SW = (\pi_1 + \pi_2) + (\Pi_1 + \Pi_2) + (CS_1 + CS_2)$. The equilibrium concession fee and terminal operator charge can be solved as:

$$\tilde{\phi}_{(g)i} = -\frac{1}{3}(2V + t) + x\left[\max\left\{0,\ D - \eta\left(I^a_i + I^t_i\right)\right\} - \frac{1}{3}\max\left\{0,\ D - \eta\left(I^a_j + I^t_j\right)\right\}\right] \tag{10.3}$$

$$\tilde{p}_{(g)i} = 0 \tag{10.4}$$

Similar to the case of private port authorities, we have $\bar{\phi}_{(g)i} < \tilde{\phi}_{(g)i}$ and $\bar{p}_{(g)i} < \tilde{p}_{(g)i}$, suggesting that the inter-port competition lowers the port concession fee and terminal charge. Moreover, we find $\bar{\phi}_{(g)i} < \bar{\phi}_i$ and $\tilde{\phi}_{(g)i} < \tilde{\phi}_i$; $\bar{p}_{(g)i} < \bar{p}_i$ and

[25] The proofs of all the derivations with public port authorities are similar (in approaches) to those of private port authorities (i.e., Section 3). To save space, the detailed proofs are not included in the paper but are available upon request from the authors.

$\tilde{p}_{(g)i} < \tilde{p}_i$, indicating that public port authorities lead to lower concession fees and terminal operator charges than those of private port authorities. This result is stated as Lemma 3.

Lemma 3. *Conditional on the port adaptations, the public port authorities lead to lower port concession fees and terminal charges.*

This result is expected as that the public port authorities care about shippers' surplus and thus charge lower concession fees so as to induce lower service charges by terminal operators (to shippers). We note further that the competing public port authorities charge lower concession fees than the monopoly authority; this is in an effort to attract shippers in the common hinterland.

5.2. Public port authorities' adaptation

Analogously to the cases of private port authorities, we solve the equilibrium port adaptation investments with public port authorities while considering the three regimes, namely, two port authorities compete with each other, two ports are under a monopoly authority, and two ports compete but have intra-port coordination between the port authority and terminal operator in adaptation investment.

At the adaptation investment stage, the competing port authorities maximize an expected regional welfare by choosing their own adaptation: $\max\limits_{I^a_{(g)i}} E[SW_i]$; $st.\ \eta(I^a_{(g)i} + I^t_{(g)i}) \le D$. For the terminal operators, they maximize expected profit: $\max\limits_{I^a_{(g)i}} E[\Pi_i]$; $st.\ \eta(I^a_{(g)i} + I^t_{(g)i}) \le D$. The equilibrium port adaptations $\bar{I}^a_{(g)i}$, $\bar{I}^t_{(g)i}$ are as follows:

$$\bar{I}^a_{(g)i} = \frac{\eta\left\{[(V + 0.21\ t)\ \Omega - D\Psi]\omega - 0.006\Psi\Omega\eta^2\right\}}{\omega\left(0.71\omega t - 3.28\ \Psi\eta^2\right)}$$

$$\bar{I}^t_{(g)i} = \frac{\eta\left\{[(V + 0.21\ t)\ \Omega - D\Psi]\omega + 0.002\Psi\Omega\eta^2\right\}}{\omega\left(0.31\omega t - 1.44\ \Psi\eta^2\right)}$$

The monopoly public port authority maximizes expected welfare of the two-port system: $\max\limits_{I^a_{(g)i}, I^a_{(g)j}} E[SW]$; $st.\ \eta(I^a_{(g)i} + I^t_{(g)i}) \le D$. And the terminal operators maximize expected profit: $\max\limits_{I^a_{(g)i}} E[\Pi_i]$; $st.\ \eta(I^a_{(g)i} + I^t_{(g)i}) \le D$. The equilibrium adaptations $\tilde{I}^a_{(g)i}$ and $\tilde{I}^t_{(g)i}$ are as follows:

$$\tilde{I}^a_{(g)i} = \frac{\eta\ [(2V + t)\ \Omega - 2D\Psi]}{2\left(\omega t - 3\ \Psi\eta^2\right)};\ \tilde{I}^t_{(g)i} = \frac{\eta\ [(2V + t)\ \Omega - 2D\Psi]}{\omega t - 3\ \Psi\eta^2}$$

For the competing port authorities with intra-port coordination, the public port authority and terminal operator of a port jointly determine adaptation to maximize the (expected) regional welfare: $\max\limits_{I^a_i, I^t_i} E[SW_i]$; s.t. $\eta(I^a_i + I^t_i) \le D$. The equilibrium adaptations $\hat{I}^a_{(g)i}$ and $\hat{I}^t_{(g)i}$ are as follows:

$$\hat{I}^a_{(g)i} = \hat{I}^t_{(g)i} = \frac{\eta\ [(V + 0.21t)\Omega - D\Psi]}{0.71\omega t - 2\ \Psi\eta^2}$$

It can be shown that the result in Proposition 2 also holds in the present case: the port adaptations with public authorities increase with a higher expectation, but decrease with a higher variance of disaster occurrence probability: i.e., $\frac{\partial\bar{I}^a_{(g)i}}{\partial\Omega} \ge 0$, $\frac{\partial\bar{I}^t_{(g)i}}{\partial\Omega} \ge 0$, $\frac{\partial\bar{I}^a_{(g)i}}{\partial\Sigma} \le 0$, $\frac{\partial\bar{I}^t_{(g)i}}{\partial\Sigma} \le 0$; $\frac{\partial\tilde{I}^a_{i(g)}}{\partial\Omega} \ge 0$, $\frac{\partial\ \tilde{I}^t_{i(g)}}{\partial\Omega} \ge 0$, $\frac{\partial\tilde{I}^a_{i(g)}}{\partial\Sigma} \le 0$, $\frac{\partial\ \tilde{I}^t_{i(g)}}{\partial\Sigma} \le 0$; $\frac{\partial\hat{I}^a_{i(g)}}{\partial\Omega} \ge 0$, $\frac{\partial\hat{I}^t_{i(g)}}{\partial\Omega} \ge 0$, $\frac{\partial\hat{I}^a_{i(g)}}{\partial\Sigma} \le 0$ and $\frac{\partial\hat{I}^t_{i(g)}}{\partial\Sigma} \le 0$.

In addition, the competition effect still exists in the case of public port authorities: i.e., $\bar{I}^a_{(g)i} > \tilde{I}^a_{(g)i}$ and $\bar{I}^t_{(g)i} > \tilde{I}^t_{(g)i}$. However, there is no free-riding effect; this is because the coordination between the public port authority and the terminal operator would reduce, instead of increasing, the adaptations: i.e., $\bar{I}^a_{(g)i} > \hat{I}^a_{(g)i}$ and $\bar{I}^t_{(g)i} > \hat{I}^t_{(g)i}$. This finding is summarized in Proposition 7:

Proposition 7. *For the public port authorities, the competition effect still exists. However, there is no free-riding between the public port authority and terminal operator in port adaptation.*

There is no free-riding effect for the case of competing public port authorities, as a public port authority aims to maximize regional welfare that includes its terminal operator's profit and invests more in adaptation as a result. This is because the public port authority has to account for the less incentive of a private terminal operator to adapt, thus investing enough adaptation to overcome the free-riding. However, when the public port authority can coordinate with its private terminal operator, together they reduce the adaptation investment so as to jointly maximize the regional welfare.

It is also found that public ownership of port authorities leads to higher adaptation investments than those under private port authorities. Specifically, the case of competing public port authorities represents the largest adaptations $\bar{I}^a_{(g)i}$ among all

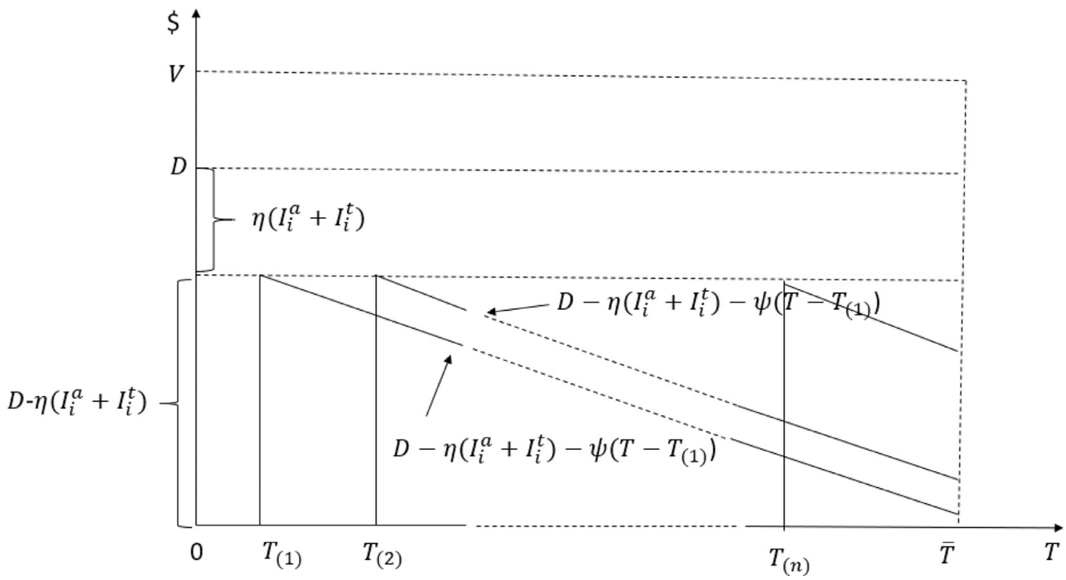

Fig. 6. Poisson jump disaster occurrence during the period $[0, \bar{T}]$ at the operation stage.

the cases. This finding verifies the empirical observation in Becker et al. (2012) that public ports are more active to invest port adaptation. We note, however, that adaptations of a monopoly public port authorities $\tilde{I}^a_{(g)i}$ and the competing public authorities with intra-port coordination $\hat{I}^a_{(g)i}$ cannot be ranked analytically.

$$\bar{I}^a_{(g)i} > \tilde{I}^a_{(g)i}, \hat{I}^a_{(g)i} > \hat{I}^a_i > \bar{I}^a_i > \tilde{I}^a_i$$

$$\bar{I}^t_{(g)i} > \tilde{I}^t_{(g)i}, \hat{I}^t_{(g)i} > \hat{I}^t_i > \bar{I}^t_i > \tilde{I}^t_i$$

The welfare ranking for the case of public port authorities cannot be obtained analytically. But the numerical simulation can be done to show that public ownership of port authorities and the resultant larger port adaptation does not always lead to higher welfare (Appendix E). For example, although the competing public port authorities lead to the highest adaptation, it can result in a lower welfare than that under the private port authorities. We summarize this finding as Proposition 8.

Proposition 8. *Public port authorities always lead to larger port adaptation investments, but it may not necessarily result in higher expected social welfare than that under private port authorities.*

The lower welfare result arises because, without intra-port coordination, public ownership of port authorities can cause an excessive amount of adaptation than the social optimum level. As the terminal operators are private, the public port authorities have to compensate the lower adaptation incentive of private terminal operators, which may result in investing too much adaptation than would be under intra-port coordination, leading to a lower welfare.

To summarize, we find the effects of Knightian uncertainty of disaster occurrence probability are almost consistent when considering the public port authorities. In the revised manuscript, we have updated the introduction and conclusion to summarize our findings regarding the public port authorities.

6. Poisson jump process of disaster occurrence

In this section, we relax our Bernoulli trial assumption of disaster occurrence at the operation stage. Specifically, we consider that the shippers and terminal operators sign a contract for a period of $\bar{T}$ length, and disaster occurrence has a Poisson jump process during this operation period $\bar{T}$. During the period, the shippers commit to use the service of port i, and pay terminal service charge p_i (which is fixed during the contract period). After the contract terminates at the end of period $\bar{T}$, shippers can re-negotiate the contract and contemplate whether to change the port. At the operation stage, one shipper's shipment is assumed to be uniformly distributed along period $[0, \bar{T}]$, with the constant utility V at each time point $T \in [0, \bar{T}]$, and the density is 1 as shown in Fig. 6. The number of disaster occurrence $N(\bar{T}) = n$ is random and follows a Poisson jump process with parameter λ. The probability function of $N(\bar{T})$ is as follows:

$$\mathrm{P}\left(N\left(\bar{T}\right) = n\right) = e^{-\lambda\bar{T}} \frac{\left(\lambda\bar{T}\right)^n}{n!} \tag{11}$$

and the expectation and variance of $N(\bar{T})$ are $\mathrm{E}(N(\bar{T}))=\lambda\bar{T}, \mathrm{Var}(N(\bar{T}))=\lambda\bar{T}$. Suppose that disaster occurs n times during the period $\bar{T}$, and let $T_{(r)}$ denote the time of the r^{th} disaster occurrence. The r^{th} disaster occurrence causes an immediate disaster damage cost $D-\eta(I^a_{(\lambda)i}+I^t_{(\lambda)i})$ to shippers at the time point $T_{(r)}$ (here we use $I^a_{(\lambda)i}$ and $I^t_{(\lambda)i}$ to differentiate them with the adaptation investments with the Bernoulli disaster occurrence, i.e., I^a_i and I^t_i). The r^{th} disaster occurrence's damage fades away at a rate of β. Thus, at a time T later than $T_{(r)}$, the damage is $[D-\eta(I^a_i+I^t_i)]-\beta(T-T_{(r)})$ caused by the r^{th} disaster occurrence. To simplify our model while keeping the major economic trade-offs, we assume the first disaster occurrence will continue to cause damage till the period ends at $\bar{T}$, i.e., $[D-\eta(I^a_i+I^t_i)]-\beta(\bar{T}-T_{(1)})>0$.

We thus can obtain total damage caused by the r^{th} disaster occurrence at the operation stage as follows:

$$C_{i(r)}=\int_{T_{(r)}}^{\bar{T}}\left[D-\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)-\beta\left(T-T_{(r)}\right)\right]dT=\left(D-\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)-\tfrac{1}{2}\beta\bar{T}\right)\bar{T}-\left(D-\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)-\beta\bar{T}\right)T_{(r)}-\tfrac{1}{2}\beta {T_{(r)}}^2 \tag{12}$$

Therefore, if there are n times of disasters occurring during the period $\bar{T}$, the shipper's total damage cost is the summation of all the disasters' cost, expressed as follows:

$$C_i=\left[D-\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)-\frac{1}{2}\beta\bar{T}\right]\bar{T}n-\left[D-\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)-\beta\bar{T}\right]\sum_{r=1}^{n}T_{(r)}-\frac{1}{2}\beta\sum_{r=1}^{n}{T_{(r)}}^2 \tag{13}$$

Conditional on $(\bar{T})=n$, the disaster occurrence times $T_{(1)}, T_{(2)},\dots, T_{(n)}$ can be proved to be independently and uniformly distributed on $[0,\bar{T}]^n$. This is equivalent that $U_{(1)}, U_{(2)},\dots, U_{(n)}$ are independently uniformly distributed on $[0, 1]^n$, with $T_{(r)}=U_{(r)}\bar{T}$. $U_{(r)}$ follows a Beta distribution as:

$$U_{(r)}\sim \mathrm{Beta}(r,\ n-r+1),\ \text{where}\ r\in\{1,2,\dots,n\}$$

Then, we have:

$$\mathrm{E}\left(U_{(r)}|\ n\right)=\frac{r}{n+1}$$

$$\mathrm{Var}\left(U_{(r)}|\ n\right)=\frac{r(n-r+1)}{(n+2)(n+1)^2}$$

$$\mathrm{E}\left({U_{(r)}}^2|\ n\right)=\mathrm{E}\left(U_{(r)}|\ n\right)^2+\mathrm{Var}\left(U_{(r)}|\ n\right)$$

Conditional on $N(\bar{T})=n$, the shipper's expected disaster damage cost over the period $[0,\bar{T}]$ is:

$$\begin{aligned}E(C_i|\ n)&=\left(D-\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)-\frac{1}{2}\beta\bar{T}\right)\bar{T}n-\left(D-\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)-\beta\bar{T}\right)E\left[\sum_{r=1}^{n}T_{(r)}|\ n\right]-\frac{1}{2}\beta E\left[\sum_{r=1}^{n}{T_{(r)}}^2|\ n\right]\\&=\left(D-\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)-\frac{1}{2}\beta\bar{T}\right)\bar{T}n-\left(D-\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)-\beta\bar{T}\right)\bar{T}\sum_{r=1}^{n}E\left(U_{(r)}|n\right)-\frac{1}{2}\beta{U_{(r)}}^2\bar{T}^2\sum_{r=1}^{n}E\left({U_{(r)}}^2|n\right)\\&=\frac{1}{6}n\bar{T}\left\{3\left[D-\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)\right]-\beta\bar{T}\right\}=\frac{1}{6}n\bar{T}\left\{\left(3D-\beta\bar{T}\right)-3\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)\right\}\end{aligned} \tag{14}$$

The proof of the above expression Eq. (14) can be found in Appendix F. The unconditional expected disaster damage cost over the period $[0,\bar{T}]$ is:

$$E(C_i)=E[E(C_i|\ n)]=\frac{1}{6}\lambda\bar{T}\left\{\left(3D-\beta\bar{T}\right)-3\eta\left(I^a_{(\lambda)i}+I^t_{(\lambda)i}\right)\right\} \tag{15}$$

Analogous to our earlier set-up, we adopt an infinite linear city to model the shippers' demand, where shippers are assumed to be uniformly distributed on the linear city with density 1 (Fig. 7). Shippers incur a cost of t per unit distance to transport cargo from its location to the port. For a shipper located at a point z in the two ports' common hinterland, the utility of using port 1 is $\int_0^{\bar{T}}VdT-\int_0^{\bar{T}}p_1dT-E(C_1)-\int_0^{\bar{T}}tzdT=V\bar{T}-p_1\bar{T}-E(C_1)-zt\bar{T}$, and the utility of using port 2 is $\int_0^{\bar{T}}VdT-\int_0^{\bar{T}}p_2dT-E(C_2)-\int_0^{\bar{T}}t(1-z)dT=V\bar{T}-p_2\bar{T}-E(C_2)-(1-z)t\bar{T}$. For a shipper located at a point z in port 1's own (captive) hinterland, the utility is $\int_0^{\bar{T}}VdT-\int_0^{\bar{T}}p_1dT-E(C_1)-\int_0^{\bar{T}}t|z|dT=V\bar{T}-p_1\bar{T}-E(C_1)-|z|t\bar{T}$. For a shipper located at a point z in port 2's own hinterland, the utility is $\int_0^{\bar{T}}VdT-\int_0^{\bar{T}}p_2dT-E(C_2)-\int_0^{\bar{T}}t(z-1)dT=V\bar{T}-p_2\bar{T}-E(C_2)-(z-1)t\bar{T}$. We can then derive the marginal shipper's location z^l, who is indifferent between using port 1's service and not using the port service at

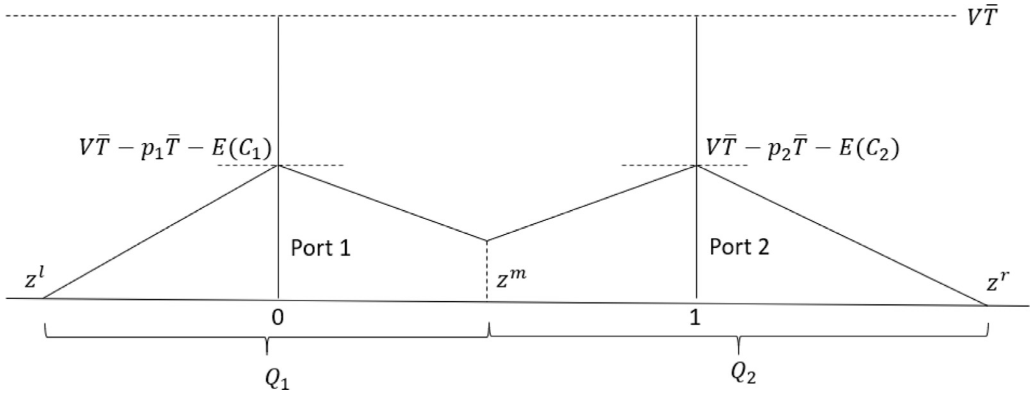

Fig. 7. Shipper's utility at each port after completion of adaptation investments (with Poisson jump disaster occurrence at the operation stage).

all; the marginal shipper's location z^m, who is indifferent between using port 1 and using port 2's service; and the marginal shipper's location z^r, who is indifferent from using port 2's service or not using the port service.

$$\left|z^l\right| = \frac{V - p_1 - \frac{1}{6}\lambda\left[\left(3D - \beta\bar{T}\right) - 3\eta\left(I^a_{(\lambda)1} + I^t_{(\lambda)1}\right)\right]}{t} \tag{16.1}$$

$$z^r = 1 + \frac{V - p_2 - \frac{1}{6}\lambda\left[\left(3D - \psi\bar{T}\right) - 3\eta\left(I^a_{(\lambda)2} + I^t_{(\lambda)2}\right)\right]}{t} \tag{16.2}$$

$$z^m = \frac{1}{2} + \frac{p_2 - p_1 - \frac{1}{6}\lambda\left[\left(3D - \psi\bar{T}\right) - 3\eta\left(I^a_{(\lambda)1} + I^t_{(\lambda)1}\right)\right] + \frac{1}{6}\lambda\left[\left(3D - \psi\bar{T}\right) - 3\eta\left(I^a_{(\lambda)2} + I^t_{(\lambda)2}\right)\right]}{2t} \tag{16.3}$$

The demand for each port at the operation stage is as follows, with $Q_1(p) = |z^l| + z^m$ and $Q_2(p) = (1 - z^m) + (z^r - 1)$:

$$Q_i(p) = \frac{1}{2} + \frac{2V + p_j - 3p_i + \frac{1}{6}\lambda\left[\left(3D - \beta\bar{T}\right) - 3\eta I^a_{(\lambda)j} + I^t_{(\lambda)j}\right] - \frac{1}{2}\lambda\left[\left(3D - \beta\bar{T}\right) - 3\eta\left(I^a_{(\lambda)i} + I^t_{(\lambda)i}\right)\right]}{2t} \tag{17}$$

6.1. Port pricing

We can solve the equilibrium concession fee of the competing port authorities and the terminal operator charge conditional on the port adaptation investments as:

$$\bar{\phi}_{(\lambda)i} = 0.23(2V + t) - \lambda\left[0.076\left(3D - \beta\bar{T}\right) - 0.25\eta\left(I^a_{(\lambda)i} + I^t_{(\lambda)i}\right) + 0.0225\eta\left(I^a_{(\lambda)j} + I^t_{(\lambda)j}\right)\right] \tag{18.1}$$

$$\bar{p}_{(\lambda)i} = 0.34(2V + t) - \lambda\left[0.112\left(3D - \beta\bar{T}\right) - 0.37\eta\left(I^a_{(\lambda)i} + I^t_{(\lambda)i}\right) + 0.033\eta\left(I^a_{(\lambda)j} + I^t_{(\lambda)j}\right)\right] \tag{18.2}$$

The equilibrium concession fee of the monopoly port authority and terminal operator charge conditional on the port adaptation investments are:

$$\tilde{\phi}_{(\lambda)i} = 0.25(2V + t) - 0.083\lambda\left[\left(3D - \beta\bar{T}\right) - 3\eta\left(I^a_{(\lambda)i} + I^t_{(\lambda)i}\right)\right] \tag{19.1}$$

$$\tilde{p}_{(\lambda)i} = 0.35(2V + t) - \lambda\left[0.116\left(3D - \beta\bar{T}\right) - 0.369\eta\left(I^a_{(\lambda)i} + I^t_{(\lambda)i}\right) + 0.021\eta\left(I^a_{(\lambda)j} + I^t_{(\lambda)j}\right)\right] \tag{19.2}$$

Similar to Lemma 1 and 2, with Poisson jump disaster occurrence at the operation stage, we also find that inter-port competition between two port authorities leads to lower concession fee and lower terminal operator charge. For ports with competing port authorities, concession fee and terminal operator charge increase with own port's adaptation but decrease with the other port's adaptation. For monopoly port authority, concession fee and terminal operator charge also increase with own port's adaptation, while not affected by the other port's adaptation. Proposition 1 also holds that an increased port adaptation at either port would enlarge the difference in concession fee and terminal operator charge between the ports.

Table 3
The summary of the equilibrium port adaptations with Poisson jump disaster occurrence at the operation stage (Known Poisson parameter λ at the adaptation investment stage).

Regimes	Port authority adaptation	Terminal operator adaptation	SOCs and finite level of adaptation	Interior solution requirement
Competing Port Authorities	$\bar{I}^{a}_{(\lambda)i} = \frac{\eta\lambda\,[(V+0.5t)-0.5(D-0.333\beta\bar{T})\lambda]}{6.1\omega t-3\lambda^2\eta^2}$	$\bar{I}^{t}_{(\lambda)i} = \frac{\eta\lambda\,[(V+0.5t)-0.5(D-0.333\beta\bar{T})\lambda]}{2.1(6.1\omega t-3\lambda^2\eta^2)}$	$\omega > 0.123\,\frac{\eta^2\lambda^2}{t}$	$\omega \geq \frac{0.24\lambda(V+0.5t)\eta^2}{Dt}$
Monopoly Port Authority	$\tilde{I}^{a}_{(\lambda)i} = \frac{\eta\lambda\,[(V+0.5t)-0.5(D-0.333\beta\bar{T})\lambda]}{6.7\omega t-0.75\lambda^2\eta^2}$	$\tilde{I}^{t}_{(\lambda)i} = \frac{\eta\lambda\,[(V+0.5t)-0.5(D-0.333\beta\bar{T})\lambda]}{13.7\,\omega t-1.525\,\lambda^2\eta^2}$	$\omega > 0.112\,\frac{\eta^2\lambda^2}{t}$	$\omega \geq \frac{0.22\lambda(V+0.5t)\eta^2}{Dt}$
Competing Port Authorities with Intra-port Coordination	$\hat{I}^{a}_{(\lambda)i} = \frac{\eta\lambda[(V+0.5t)-0.5(D-0.333\beta\bar{T})\lambda]}{4.1\omega t-\lambda^2\eta^2}$	$\hat{I}^{t}_{(\lambda)i} = \frac{\eta\,[(V+0.5t)\,\Omega-0.5(D-0.333\beta\bar{T})\Psi]}{4.1\omega t-\lambda^2\eta^2}$	$\omega > 0.245\,\frac{\eta^2\lambda^2}{t}$	$\omega \geq \frac{0.48\lambda(V+0.5t)\eta^2}{Dt}$

Moreover, Poisson parameter λ and operation stage length $\bar{T}$ also affect port pricing conditional on port adaptation investments, with Lemma 4.1 and Lemma 4.2 summarized as follows:[26]

Lemma 4.1. *The concession fee and terminal operator charge decrease with λ and increase with $\bar{T}$.*

Lemma 4.2. *The differences in both the concession fees and terminal operator charges between the competing and monopoly port authorities regimes decrease with λ and increase with $\bar{T}$.*

When λ increases, shipper would expect more frequent and more volatile disaster occurrences during the operation stage, such that port authorities and terminal operators are forced to lower the prices to attract shippers. This effect is stronger for the monopoly port authority, where their market powers are more adversely affected by more frequent and volatile disaster occurrences, and more positively affected by operation stage length $\bar{T}$.

6.2. Port adaptation

To solve for the equilibrium adaptation investments by port authorities and terminal operators, we consider two cases where Poisson parameter λ is known at the adaptation investment stage, or is a random variable representing a Knightian uncertainty on λ.

6.2.1. Known Poisson parameter $\boldsymbol{\lambda}$

When Poisson parameter λ is known at the adaptation investment stage, the equilibrium adaptation investments by the port authorities and terminal operators can be solved as summarized in Table 3. First, we still have the relationship: $\bar{I}^{a}_{(\lambda)i} \geq \tilde{I}^{a}_{(\lambda)i}$; $\bar{I}^{t}_{(\lambda)i} \geq \tilde{I}^{t}_{(\lambda)i}$ and $\hat{I}^{a}_{(\lambda)i} \geq \bar{I}^{a}_{(\lambda)i}$; $\hat{I}^{t}_{(\lambda)i} \geq \bar{I}^{t}_{(\lambda)i}$, such that the competition effect and the free-riding effects still exist, consistent with Proposition 3 in Section 3.

Additionally, it can be shown that:

$$\frac{\partial \bar{I}^{a}_{(\lambda)i}}{\partial \lambda} \geq 0;\ \frac{\partial \tilde{I}^{a}_{(\lambda)i}}{\partial \lambda} \geq 0;\ \frac{\partial \hat{I}^{a}_{(\lambda)i}}{\partial \lambda} \geq 0 \text{ and } \frac{\partial \bar{I}^{t}_{(\lambda)i}}{\partial \lambda} \geq 0;\ \frac{\partial \tilde{I}^{t}_{(\lambda)i}}{\partial \lambda} \geq 0;\ \frac{\partial \hat{I}^{t}_{(\lambda)i}}{\partial \lambda} \geq 0$$
$$\frac{\partial \bar{I}^{a}_{(\lambda)i}}{\partial \bar{T}} \geq 0;\ \frac{\partial \tilde{I}^{a}_{(\lambda)i}}{\partial \bar{T}} \geq 0;\ \frac{\partial \hat{I}^{a}_{(\lambda)i}}{\partial \bar{T}} \geq 0 \text{ and } \frac{\partial \bar{I}^{t}_{(\lambda)i}}{\partial \bar{T}} \geq 0;\ \frac{\partial \tilde{I}^{t}_{(\lambda)i}}{\partial \bar{T}} \geq 0;\ \frac{\partial \hat{I}^{t}_{(\lambda)i}}{\partial \bar{T}} \geq 0$$

The above comparative statics lead to Proposition 9 concerning the effect the Poisson parameter λ and the operation stage length $\bar{T}$ on port adaptation investments:

Proposition 9. *When the Poisson parameter is known at the adaptation investment stage, the ports adapt more when λ is larger, i.e., the expectation and variance of the Poisson jump disaster occurrence are larger at the operation stage. In addition, the ports invest more in adaptation when $\bar{T}$ is larger, i.e., when the port authorities and terminal operators sign a contract effective for a longer period.*

It should be noted that Poisson parameter λ also indicates the variance of the number of disaster occurence at the operation stage, which measures the disaster uncertainty at the operation stage. When the port authorities and terminal operators have perfect information on the value of λ at the adaptation investment stage, the port increases adaptation investment with λ because the shippers dislike larger variability in disaster occurrence at the operation stage. As a result, this disaster uncertainty at the operation stage encourages port adaptation investment at the adaptation investment stage.

However, as we will show later, when the port authorities and terminal operators have Knightian uncertainty on the value of λ at the adaptation investment stage, such uncertainty on λ discourages port adaptation. This is because it is the

[26] The proofs of the findings are in a very similar way as of the earlier sections with Bernoulli disaster occurrence at the operation stage. To save space, we did not report the details in the manuscript, while they are available upon request.

Table 4
The summary of the equilibrium port adaptation with Poisson jump disaster occurrence at the operation stage (Knightian uncertain Poisson parameter **λ** at the adaptation investment stage).

Regimes	Port authority adaptation	Terminal operator adaptation	SOCs and finite level of adaptation	Interior solution requirement
Competing Port Authorities	$\bar{I}^{a}_{(\lambda)i} = \frac{\eta\lambda\,[(V+0.5t)-0.5(D-0.333\beta\bar{T})\Lambda]}{6.1\omega t-3\Gamma\eta^2}$	$\bar{I}^{t}_{(\lambda)i} = \frac{\eta\lambda\,[(V+0.5t)-0.5(D-0.333\beta\bar{T})\Lambda]}{2.1(6.1\omega t-3\Gamma\eta^2)}$	$\omega > 0.123\ \frac{\eta^2\Gamma}{t}$	$\omega \geq \frac{0.24\lambda(V+0.5t)\Gamma}{Dt}$
Monopoly Port Authority	$\tilde{I}^{a}_{(\lambda)i} = \frac{\eta\lambda\,[(V+0.5t)-0.5(D-0.333\beta\bar{T})\Lambda]}{6.7\omega t-0.75\Gamma\eta^2}$	$\tilde{I}^{t}_{(\lambda)i} = \frac{\eta\lambda\,[(V+0.5t)-0.5(D-0.333\beta\bar{T})\Lambda]}{13.7\ \omega t-1.525\Gamma\eta^2}$	$\omega > 0.112\ \frac{\eta^2\Gamma}{t}$	$\omega \geq \frac{0.22\lambda(V+0.5t)\Gamma}{Dt}$
Competing Port Authorities with Intra-port Coordination	$\hat{I}^{a}_{(\lambda)i} = \frac{\eta\lambda[(V+0.5t)-0.5(D-0.333\beta\bar{T})\Lambda]}{4.1\omega t-\Gamma\eta^2}$	$\hat{I}^{t}_{(\lambda)i} = \frac{\eta\,[(V+0.5t)\ \Omega-0.5(D-0.333\beta\bar{T})\Lambda]}{4.1\omega t-\Gamma\eta^2}$	$\omega > 0.245\ \frac{\eta^2\Gamma}{t}$	$\omega \geq \frac{0.48\lambda(V+0.5t)\Gamma}{Dt}$

ports that bear all the risk of adaptation investment. They thus tend to invest less with higher Knightian uncertainty on λ at the adaptation investment stage.

In addition, we find port invest more when the contract period $\bar{T}$ is longer, which is because the one-time adaptation investment can have more value to reduce shipper's damage within a longer period, giving ports more incentive to invest adaptation.

We also find that $\frac{\partial}{\partial\lambda}\left(\frac{\bar{I}^{a}_{(\lambda)i}}{\tilde{I}^{a}_{(\lambda)i}}\right) > 0$, $\frac{\partial}{\partial\lambda}\left(\frac{\bar{I}^{t}_{(\lambda)i}}{\tilde{I}^{t}_{(\lambda)i}}\right) > 0$ and $\frac{\partial}{\partial\lambda}\left(\frac{\hat{I}^{a}_{(\lambda)i}}{\bar{I}^{a}_{(\lambda)i}}\right) > 0$, $\frac{\partial}{\partial\lambda}\left(\frac{\hat{I}^{t}_{(\lambda)i}}{\bar{I}^{t}_{(\lambda)i}}\right) > 0$, while $\frac{\partial}{\partial\bar{T}}\left(\frac{\bar{I}^{a}_{(\lambda)i}}{\tilde{I}^{a}_{(\lambda)i}}\right) = 0$, $\frac{\partial}{\partial\bar{T}}\left(\frac{\bar{I}^{t}_{(\lambda)i}}{\tilde{I}^{t}_{(\lambda)i}}\right) = 0$ and $\frac{\partial}{\partial\lambda}\left(\frac{\hat{I}^{a}_{(\lambda)i}}{\bar{I}^{a}_{(\lambda)i}}\right) = 0$, $\frac{\partial}{\partial\lambda}\left(\frac{\hat{I}^{t}_{(\lambda)i}}{\bar{I}^{t}_{(\lambda)i}}\right) = 0$. These lead to the following proposition:

Proposition 10. *When the Poisson parameter is known at the adaptation investment stage, the competition effect and the free-riding effect are strengthened by larger λ, i.e., a larger expectation and variance of the number of disaster occurrences at the operation stage.*

6.2.2. Knightian uncertain Poisson parameter λ

When Poisson parameter λ is unknown at the adaptation investment stage (which follows a random distribution), the port authorities and terminal operators face a Knightian uncertainty on λ. Let $h(\lambda)$ denote the pdf of λ, and λ has the expectation Λ, the variance ϒ, and the second moment $\Gamma = \Lambda + \Upsilon$. With similar procedures as in Section 3, we derive the equilibrium adaptation investments by port authorities and terminal operators as summarized in Table 4.

It can be shown that:

$$\frac{\partial\bar{I}^{a}_{(\lambda)i}}{\partial\Lambda} \geq 0;\ \frac{\partial\tilde{I}^{a}_{(\lambda)i}}{\partial\Lambda} \geq 0;\ \frac{\partial\hat{I}^{a}_{(\lambda)i}}{\partial\Lambda} \geq 0 \text{ and } \frac{\partial\bar{I}^{t}_{(\lambda)i}}{\partial\Lambda} \geq 0;\ \frac{\partial\tilde{I}^{t}_{(\lambda)i}}{\partial\Lambda} \geq 0;\ \frac{\partial\hat{I}^{t}_{(\lambda)i}}{\partial\Lambda} \geq 0$$
$$\frac{\partial\bar{I}^{a}_{(\lambda)i}}{\partial\Upsilon} \leq 0;\ \frac{\partial\tilde{I}^{a}_{(\lambda)i}}{\partial\Upsilon} \leq 0;\ \frac{\partial\hat{I}^{a}_{(\lambda)i}}{\partial\Upsilon} \leq 0 \text{ and } \frac{\partial\bar{I}^{t}_{(\lambda)i}}{\partial\Upsilon} \leq 0;\ \frac{\partial\tilde{I}^{t}_{(\lambda)i}}{\partial\Upsilon} \leq 0;\ \frac{\partial\hat{I}^{t}_{(\lambda)i}}{\partial\Upsilon} \leq 0$$

Therefore, Proposition 2 still hold: for a Knightian uncertain Poisson parameter λ at the adaptation investment stage, the port adaptation increases with Λ (the expectation of λ), while decreases with ϒ (the variance of λ). This indicates that an increasing ambiguity on the Poisson parameter discourages the port adaptation investment, because the port authorities and terminal operators have to bear all the risk to invest excessively at the adaptation investment stage.

In addition, we still reach the relationships $\bar{I}^{a}_{(\lambda)i} \geq \tilde{I}^{a}_{(\lambda)i}$; $\bar{I}^{t}_{(\lambda)i} \geq \tilde{I}^{t}_{(\lambda)i}$ and $\hat{I}^{a}_{(\lambda)i} \geq \bar{I}^{a}_{(\lambda)i}$; $\hat{I}^{t}_{(\lambda)i} \geq \bar{I}^{t}_{(\lambda)i}$ such that the competition and free-riding effects also exist with Knightian uncertain Poisson parameter λ at adaptation investment stage. Moreover, $\frac{\partial}{\partial\Lambda}\left(\frac{\bar{I}^{a}_{(\lambda)i}}{\tilde{I}^{a}_{(\lambda)i}}\right) > 0$, $\frac{\partial}{\partial\Upsilon}\left(\frac{\bar{I}^{a}_{(\lambda)i}}{\tilde{I}^{a}_{(\lambda)i}}\right) > 0$ and $\frac{\partial}{\partial\Lambda}\left(\frac{\bar{I}^{t}_{(\lambda)i}}{\tilde{I}^{t}_{(\lambda)i}}\right) > 0$, $\frac{\partial}{\partial\Upsilon}\left(\frac{\bar{I}^{t}_{(\lambda)i}}{\tilde{I}^{t}_{(\lambda)i}}\right) > 0$, indicating that the competition effect is also strengthened by the expectation of Poisson parameter λ; and $\frac{\partial}{\partial\Lambda}\left(\frac{\hat{I}^{t}_{(\lambda)i}}{\bar{I}^{t}_{(\lambda)i}}\right) > 0$, $\frac{\partial}{\partial\Upsilon}\left(\frac{\hat{I}^{t}_{(\lambda)i}}{\bar{I}^{t}_{(\lambda)i}}\right) > 0$ and $\frac{\partial}{\partial\Lambda}\left(\frac{\hat{I}^{t}_{(\lambda)i}}{\bar{I}^{t}_{(\lambda)i}}\right) > 0$, $\frac{\partial}{\partial\Upsilon}\left(\frac{\hat{I}^{t}_{(\lambda)i}}{\bar{I}^{t}_{(\lambda)i}}\right) > 0$, indicating that the free-riding effect is also reinforced by the variance of Poisson parameter λ. These results are consistent with Propositions 3 and 4. The ranking of expected social welfare is $E[\widehat{SW}_{(\lambda)}] > E[\overline{SW}_{(\lambda)}] > E[\widetilde{SW}_{(\lambda)}]$, such that Proposition 5 also holds.

It is also found that the ports increase adaptations when the port authorities and terminal operators sign a longer contract (i.e., larger $\bar{T}$). This is because the one-time adaptation investment can have more value to reduce shippers' damage for a longer period, offering ports more incentive to invest adaptation.

To summarize, we find that the competition and free-riding effects on port adaptations are robust to the assumptions of disaster occurrence (Bernoulli vs. Poisson jump process) at the operation stage. In addition, when the disaster occurrence-related parameters (disaster occurrence probability or Poisson parameter) have Knightian uncertainty, their impacts on the port adaptations are qualitatively the same.

7. Concluding remarks

With more than 80% of the global trade by value carried by international maritime shipping, coastal ports' resilience to climate change-related disasters is important to maintain a reliable global supply chain. Ports around the world are increas-

ingly aware of adaptation with respect to the threat of such disasters. This study contributes to the existing literature on port adaptation mainly in two aspects. First, we model the climate change-related disasters to have a general-form of Knightian uncertainty (Knight 1921) in the sense that the probability of the disaster occurrence is *per se* a random variable and is not accurately knowable when planning the adaptation investment projects. Our Knightian uncertainty captures a more general and wider family of probability distributions, which are not limited to the specific assumptions in Weitzman (2009) and Xiao et al. (2015). Second, we explicitly examine the impacts of inter-port competition, as well as intra-port cooperation, on port adaptation investments. The study answers how both inter-port competition and intra-port cooperation can affect the port adaptation. Apart from these two contributions, we have explicitly modeled endogenous port pricing and shippers' demand which were absent in earlier literature on port adaptation. In addition, the impact of port authorities' ownership (private vs. public) on port adaptation and that of a Poisson jump process of disaster occurrence are investigated.

We find that, with the Knightian uncertainty assumption at the adaptation investment stage, port adaptation increases with the expectation of the disaster occurrence probability but decreases with its variance. In other words, a higher expectation of the disaster occurrence probability encourages the adaptation, but a larger variance of the disaster occurrence probability discourages the adaptation. This analytical result provides an explanation for why in practice adaptation is much more difficult to implement than mitigation, as in practice the existing knowledge about climate change and associated disasters needed for adaptation is quite poor. Furthermore, when the port authorities maximize profit, inter-port competition results in more adaptation investments (i.e., the competition effect). On the other hand, there is free-riding on adaptation investments between the port authority and the terminal operator within a port (i.e. the free-riding effect); as a consequence, the intra-port coordination can, by removing the free-riding effect, increase the adaptation. We further find that the competition and free-riding effects can be strengthened by a higher expectation, and a larger variance, of the disaster occurrence probability, and by a more intense inter-port competition. When we extend our analysis to public port authorities, the free-riding effect vanishes; here, public port authorities are willing to invest more to account for the lower adaptation incentive by terminal operators. We also find that public port authorities lead to greater adaptation, but not necessarily to higher expected welfare. This is because, without intra-port coordination, public authorities may invest excessively as compared to the first-best level in order to overcome the lower adaptation incentive by private terminal operators. Finally, with the Poisson jump process of disaster occurrence during the operation stage, we show that the port pricing and price difference between the competing and monopoly port authorities decrease with the Poisson parameter. Without Knightian uncertainty in the Poisson parameter, port adaptation increases with Poisson parameter at the operation stage. When the Poisson parameter has Knightian uncertainty at the adaptation investment stage, our previous findings continue to hold.

This study also opens up several new avenues for future research. First, the market structure of private terminal operators needs better exploration. We assume each port has a single terminal operator, which can be restrictive. One port can have more than one terminal operator, either private or owned by port authority. Some shipping lines also operate dedicated terminals. In addition, multinational terminal operators such as PSA International, Hutchison Port Holding, APM terminals, DP World and China Merchant Holding can simultaneously operate in several nearby ports. Such intra- and inter-port competition, and inter-port cooperation among private terminal operators can be better accounted for in the future study when analyzing port adaptation. Second, we assume the disaster occurrence probability will become exactly known at the operation stage. However, information updating at the operation stage can only reduce variance of disaster occurrence probability but not totally eliminate the variance. A more realistic approach could be to model the other Knightian uncertain disaster probability at the operation stage but with smaller variance. The basic insights of this paper would, we believe, still prevail with this alternative approach. Future studies are thus called for with more general assumptions on the disaster occurrence probability at the operation stage, and to test the robustness of our findings. Finally, our study exclusively focuses on the disaster adaptation decision, while a port can have multi-dimensional long-term decisions, such as capacity expansion, facilities upgrading etc. With a limited resource, a port may need to trade off among adaptation, capacity expansion and other development projects. A more comprehensive model is therefore called for to consider the port optimal resource allocation for multi-dimension decisions.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.trb.2018.08.003.

Appendix A. Port pricing

Terminal operators maximize profit by setting service charge p_i to shippers. They also pay concession fee φ_i to their port authorities. The maximization of the profit function of the terminal operator is $\max_{p_i} \Pi_i = (p_i - \phi_i)Q_i$. The FOCs are:

$$\frac{\partial \Pi_i}{\partial p_i} = \frac{0.5\left[2V + t - 6p_i + 3\phi_i + p_j - 3x\text{Max}\left\{0,\ D - \eta c\left(I_i^a + I_i^t\right)\right\} + x\text{Max}\left\{0,\ D - \eta\left(I_j^a + I_j^t\right)\right\}\right]}{t} = 0$$

The SOCs are $\frac{\partial^2 \Pi_i}{\partial p_i^2} = -\frac{3}{t} < 0$.

The competing port authorities maximize their profits as $\underset{\phi_i}{\text{Max}}\ \pi_i = \phi_i Q_i(p_i(\phi_i,\ \phi_j), p_j(\phi_i,\ \phi_j))$. The FOCs are:

$$\frac{\partial \pi_i}{\partial \phi_i} = \frac{0.6\left[V + 0.5t - 2.43\phi_i + 0.219\phi_j - 1.214x\text{Max}\left\{0,\ D - \eta\left(I_i^a + I_i^t\right)\right\} + 0.214x\text{Max}\left\{0,\ D - \eta\left(I_j^a + I_j^t\right)\right\}\right]}{t} = 0$$

The SOCs are $\frac{\partial^2 \pi_i}{\partial \phi_i^2} = -\frac{1.457}{t} \le 0$.

The monopoly port authority maximizes a joint profit for the two ports as $\max_{\phi_i,\phi_j} \sum_{i=1}^{2} \pi_i = \sum_{i=1}^{2} \phi_i Q_i(p_i(\phi_i,\ \phi_j), p_j(\phi_i,\ \phi_j))$. The FOCs are expressed as follows:

$$\frac{\partial(\pi_i + \pi_j)}{\partial \phi_i} = \frac{0.6\left[V + 0.5t - 2.43\phi_i + 0.438\phi_j - 1.214x\text{Max}\left\{0,\ D - \eta\left(I_i^a + I_i^t\right)\right\} + 0.214x\text{Max}\left\{0,\ D - \eta\left(I_j^a + I_j^t\right)\right\}\right]}{t} = 0$$

The SOCs are $\frac{\partial^2(\pi_i + \pi_j)}{\partial \phi_i^2} = -\frac{1.457}{t} \le 0$.

For the competing port authorities, the FOCs satisfy $\frac{\partial \pi_i(\bar{\phi}_i,\ \bar{\phi}_j)}{\partial \phi_i} = 0$. For the monopoly port authority, the FOCs satisfy $\underbrace{\frac{\partial \pi_i(\tilde{\phi}_i,\ \tilde{\phi}_j)}{\partial \phi_i}}_{<0} + \underbrace{\frac{\partial \pi_j(\tilde{\phi}_i,\ \tilde{\phi}_j)}{\partial \phi_i}}_{>0} = 0$. With the monopoly port authority setting concession fee at one port, it internalizes the positive externality of higher concession fee on the other port i.e., $\underbrace{\frac{\partial \pi_j(\tilde{\phi}_i,\ \tilde{\phi}_j)}{\partial \phi_i}}_{>0}$ and $\underbrace{\frac{\partial \pi_i(\tilde{\phi}_i,\ \tilde{\phi}_j)}{\partial \phi_j}}_{>0}$. In addition, the second derivative $\frac{\partial^2 \pi_i(\bar{\phi}_i,\ \bar{\phi}_j)}{\partial \phi_i \partial \phi_j} > 0$, as concession fees at ports are strategic complements. The second derivative $\frac{\partial^2 \pi_i(\bar{\phi}_i,\ \bar{\phi}_j)}{\partial {\phi_i}^2} < 0$ as required by the SOC. Because of the symmetry, we have $\tilde{\phi}_i = \tilde{\phi}_j$ and $\bar{\phi}_i = \bar{\phi}_j$. It is true that $|\frac{\partial^2 \pi_i(\bar{\phi}_i,\ \bar{\phi}_j)}{\partial {\phi_i}^2}| > |\frac{\partial^2 \pi_i(\bar{\phi}_i,\ \bar{\phi}_j)}{\partial \phi_i \partial \phi_j}|$. In other words, the second derivative $\frac{\partial^2 \pi_i(\bar{\phi}_i,\ \bar{\phi}_j)}{\partial {\phi_i}^2}$ is the main effect. Because $\frac{\partial \pi_i(\bar{\phi}_i,\ \bar{\phi}_j)}{\partial \phi_i} = 0$ and $\frac{\partial \pi_i(\tilde{\phi}_i,\ \tilde{\phi}_j)}{\partial \phi_i} < 0$, we have $\tilde{\phi}_i = \tilde{\phi}_i > \bar{\phi}_i = \bar{\phi}_j$. Terminal operators' charges $p_i(\varphi_i,\varphi_j)$ and $p_j(\varphi_i,\varphi_j)$ are increasing function of φ_i and φ_j, such that $\tilde{p}_i(\tilde{\phi}_i, \tilde{\phi}_i) > \tilde{p}_i(\bar{\phi}_i, \bar{\phi}_j)$ and $\tilde{p}_j(\tilde{\phi}_i, \tilde{\phi}_i) > \tilde{p}_j(\bar{\phi}_i, \bar{\phi}_j)$.

Taking total derivatives of the FOCs of the competing port authorities with respect to I_i^a:

$$\frac{\partial^2 \pi_i\left(\bar{\phi}_i,\ \bar{\phi}_j\right)}{\partial \phi_i \partial I_i^a} + \frac{\partial^2 \pi_i\left(\bar{\phi}_i,\ \bar{\phi}_j\right)}{\partial {\phi_i}^2}\frac{\partial \bar{\phi}_i}{\partial I_i^a} + \frac{\partial^2 \pi_i\left(\bar{\phi}_i,\ \bar{\phi}_j\right)}{\partial \phi_i \partial \phi_j}\frac{\partial \bar{\phi}_j}{\partial I_i^a} = 0$$
$$\frac{\partial^2 \pi_j\left(\bar{\phi}_i,\ \bar{\phi}_j\right)}{\partial \phi_j \partial I_i^a} + \frac{\partial^2 \pi_i\left(\bar{\phi}_i,\ \bar{\phi}_j\right)}{\partial \phi_i \partial \phi_j}\frac{\partial \bar{\phi}_i}{\partial I_i^a} + \frac{\partial^2 \pi_j\left(\bar{\phi}_i,\ \bar{\phi}_j\right)}{\partial {\phi_j}^2}\frac{\partial \bar{\phi}_j}{\partial I_i^a} = 0$$

Solving $\frac{\partial \bar{\phi}_i}{\partial I_i^a}$ as follows:

$$\frac{\partial \bar{\phi}_i}{\partial I_i^a} = \frac{-\left(\frac{\partial^2 \pi_j}{\partial {\phi_j}^2}\frac{\partial^2 \pi_i}{\partial \phi_i \partial I_i^a}\right) + \left(\frac{\partial^2 \pi_i}{\partial \phi_i \partial \phi_j}\frac{\partial^2 \pi_j}{\partial \phi_j \partial I_i^a}\right)}{\frac{\partial^2 \pi_i}{\partial {\phi_i}^2}\frac{\partial^2 \pi_j}{\partial {\phi_j}^2} - \frac{\partial^2 \pi_i}{\partial \phi_i \partial \phi_j}\frac{\partial^2 \pi_j}{\partial \phi_i \partial \phi_j}} > 0$$

The denominator $\frac{\partial^2 \pi_i}{\partial {\phi_i}^2}\frac{\partial^2 \pi_j}{\partial {\phi_j}^2} - \frac{\partial^2 \pi_i}{\partial \phi_i \partial \phi_j}\frac{\partial^2 \pi_j}{\partial \phi_i \partial \phi_j}$ is positive, because $|\frac{\partial^2 \pi_i}{\partial {\phi_i}^2}| > |\frac{\partial^2 \pi_i}{\partial \phi_i \partial \phi_j}|$ and $|\frac{\partial^2 \pi_j}{\partial {\phi_j}^2}| > |\frac{\partial^2 \pi_j}{\partial \phi_i \partial \phi_j}|$. The numerator $-(\frac{\partial^2 \pi_j}{\partial {\phi_j}^2}\frac{\partial^2 \pi_i}{\partial \phi_i \partial I_i^a}) + (\frac{\partial^2 \pi_i}{\partial \phi_i \partial \phi_j}\frac{\partial^2 \pi_j}{\partial \phi_j \partial I_i^a})$ is also positive, because $|\frac{\partial^2 \pi_j}{\partial {\phi_j}^2}| > |\frac{\partial^2 \pi_i}{\partial \phi_i \partial \phi_j}|$ and $|\frac{\partial^2 \pi_i}{\partial \phi_i \partial I_i^a} > \frac{\partial^2 \pi_j}{\partial \phi_j \partial I_i^a}|$. Therefore $\frac{\partial \bar{\phi}_i}{\partial I_i^a} > 0$.

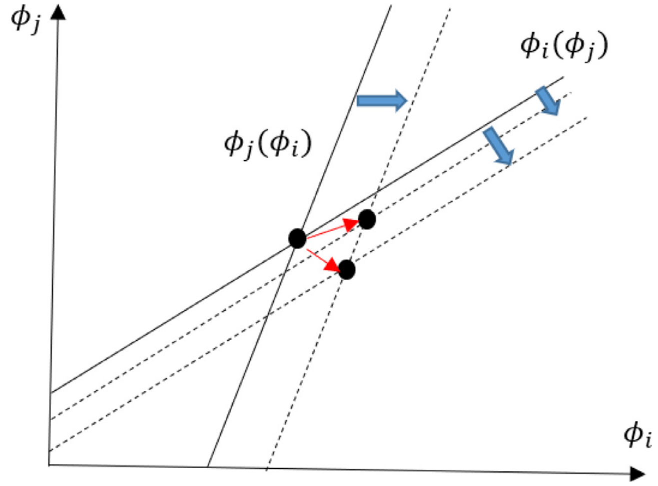

Fig. A1. The impact of increased port authority adaptation I_i^a on the best response functions of competing port authorities' concession fee at operation stage.

Solving $\frac{\partial \bar{\phi}_j}{\partial I_i^a}$ as follows:

$$\frac{\partial \bar{\phi}_j}{\partial I_i^a} = \frac{\frac{\partial^2 \pi_j}{\partial \phi_i \partial \phi_j}\frac{\partial^2 \pi_i}{\partial \phi_i \partial I_i^a} - \frac{\partial^2 \pi_i}{\partial {\phi_i}^2}\frac{\partial^2 \pi_j}{\partial \phi_j \partial I_i^a}}{\frac{\partial^2 \pi_i}{\partial {\phi_i}^2}\frac{\partial^2 \pi_j}{\partial {\phi_j}^2} - \frac{\partial^2 \pi_i}{\partial \phi_i \partial \phi_j}\frac{\partial^2 \pi_j}{\partial \phi_i \partial \phi_j}}$$

The denominator of $\frac{\partial \bar{\phi}_j}{\partial I_i^a}$ is the same as $\frac{\partial \bar{\phi}_i}{\partial I_i^a}$, which is positive. Numerator $\frac{\partial^2 \pi_j}{\partial \phi_i \partial \phi_j}\frac{\partial^2 \pi_i}{\partial \phi_i \partial I_i^a} - \frac{\partial^2 \pi_i}{\partial \phi_i \partial I_i^a}\frac{\partial^2 \pi_i}{\partial {\phi_i}^2}\frac{\partial^2 \pi_j}{\partial \phi_j \partial I_i^a}$ has uncertain sign, which depends on the relative magnitude of $\frac{\partial^2 \pi_j}{\partial \phi_i \partial \phi_j}\frac{\partial^2 \pi_i}{\partial \phi_i \partial I_i^a}$ and $\frac{\partial^2 \pi_i}{\partial {\phi_i}^2}\frac{\partial^2 \pi_j}{\partial \phi_j \partial I_i^a}$. As shown in following Fig. A1, when I_i^a increases, the BRF $\varphi_j(\varphi_i)$ moves outward, and the BRF $\varphi_i(\varphi_j)$ moves downward. If $\varphi_i(\varphi_j)$ does not move too much with I_i^a, the new equilibrium concession fees increase for both φ_i and φ_j. If $\varphi_i(\varphi_j)$ moves more with I_i^a, the new equilibrium concession fee φ_i will still increase, but concession fee φ_j will decrease. With the functional form imposed in this study, we can derive that $\frac{\partial \bar{\phi}_j}{\partial I_i^a} < 0$.

Analogously, we are able to prove $\frac{\partial \bar{\phi}_i}{\partial I_i^t} > 0$, and the sign $\frac{\partial \bar{\phi}_j}{\partial I_i^t}$ depends on the relative magnitude of $\frac{\partial^2 \pi_j}{\partial \phi_i \partial \phi_j}\frac{\partial^2 \pi_i}{\partial \phi_i \partial I_i^t}$ and $\frac{\partial^2 \pi_i}{\partial {\phi_i}^2}\frac{\partial^2 \pi_j}{\partial \phi_j \partial I_i^t}$. With our functional form, it can be derived that $\frac{\partial \bar{\phi}_j}{\partial I_i^t} < 0$.

Taking total derivatives of the FOCs of monopoly port authority with respect to I_i^a:

$$\frac{\partial^2\left(\pi_i(\tilde{\phi}_i,\ \tilde{\phi}_j) + \pi_j(\tilde{\phi}_i,\ \tilde{\phi}_j)\right)}{\partial \phi_i \partial I_i^a} + \frac{\partial^2\left(\pi_i(\tilde{\phi}_i,\ \tilde{\phi}_j) + \pi_j(\tilde{\phi}_i,\ \tilde{\phi}_j)\right)}{\partial {\phi_i}^2}\frac{\partial \tilde{\phi}_i}{\partial I_i^a} + \frac{\partial^2\left(\pi_i(\tilde{\phi}_i,\ \tilde{\phi}_j) + \pi_j(\tilde{\phi}_i,\ \tilde{\phi}_j)\right)}{\partial \phi_i \partial \phi_j}\frac{\partial \tilde{\phi}_j}{\partial I_i^a} = 0$$

$$\frac{\partial^2\left(\pi_i(\tilde{\phi}_i,\ \tilde{\phi}_j) + \pi_j(\tilde{\phi}_i,\ \tilde{\phi}_j)\right)}{\partial \phi_j \partial I_i^a} + \frac{\partial^2\left(\pi_i(\tilde{\phi}_i,\ \tilde{\phi}_j) + \pi_j(\tilde{\phi}_i,\ \tilde{\phi}_j)\right)}{\partial \phi_i \partial \phi_j}\frac{\partial \tilde{\phi}_i}{\partial I_i^a} + \frac{\partial^2\left(\pi_i(\tilde{\phi}_i,\ \tilde{\phi}_j) + \pi_j(\tilde{\phi}_i,\ \tilde{\phi}_j)\right)}{\partial {\phi_j}^2}\frac{\partial \tilde{\phi}_j}{\partial I_i^a} = 0$$

Solving $\frac{\partial \tilde{\phi}_i}{\partial I_i^a}$ as follows:

$$\frac{\partial \tilde{\phi}_i}{\partial I_i^a} = \frac{-\left(\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial \phi_j \partial I_i^a}}^{<0}\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial \phi_i \partial \phi_j}}^{>0}\right) + \overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial \phi_i \partial I_i^a}}^{>0}\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial {\phi_j}^2}}^{<0}}{\underbrace{\left(\frac{\partial^2(\pi_i+\pi_j)}{\partial \phi_i \partial \phi_j}\right)^2 - \left(\frac{\partial^2(\pi_i+\pi_j)}{\partial {\phi_i}^2}\right)\left(\frac{\partial^2(\pi_i+\pi_j)}{\partial {\phi_j}^2}\right)}_{<0}} > 0$$

The denominator $(\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\partial\phi_j})^2 - (\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2})(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_j}^2}) < 0$, as suggested by the Hessian condition for monopoly port authority to maximize profit. For the numerator, $|\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_j}^2}| > |\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\partial\phi_j}|$, and $|\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\partial I_i^a}| > |\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_j\partial I_i^a}|$, such that the numerator is positive as well.

Solving for $\frac{\partial\tilde{\phi}_i}{\partial I_j^a}$ as follows:

$$\frac{\partial\tilde{\phi}_i}{\partial I_j^a} = \frac{\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_j\partial I_i^a}}^{<0}\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2}}^{<0} - \overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\partial\phi_j}}^{>0}\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\partial I_i^a}}^{>0}}{\left(\underbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\partial\phi_j}^2 - \left(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2}\right)\left(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_j}^2}\right)}_{<0}\right)}$$

The denominator$(\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\partial\phi_j})^2 - (\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2})(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_j}^2}) < 0$. For numerator, $|\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_j\partial I_i^a}| < |\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\partial I_i^a}|$ and $|\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2}| < |\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\partial\phi_j}|$, thus the sign of the numerator is uncertain. We thus have to depend on our functional setup to determine the sign of $\frac{\partial\tilde{\phi}_i}{\partial I_j^a}$ with the result as $\frac{\partial\tilde{\phi}_i}{\partial I_j^a} = 0$.

Analogously, it can be shown that $\frac{\partial\tilde{\phi}_i}{\partial I_i^t} > 0$ and the sign of $\frac{\partial\tilde{\phi}_j}{\partial I_i^t}$ depends on the relative magnitude of $\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_j\partial I_i^a}\ \frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2}$ and $\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\partial\phi_j}\ \frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\partial I_i^a}$. The signs of derivatives of $\tilde{p}_i(\bar{\phi}_i, \bar{\phi}_j, I)$; $\tilde{p}_j(\bar{\phi}_i, \bar{\phi}_j, I)$ and $\tilde{p}_i(\tilde{\phi}_i, \tilde{\phi}_i, I)$; $\tilde{p}_j(\tilde{\phi}_i, \tilde{\phi}_i, I)$ to I_i^a and I_i^t can only be judged with functional setup.

Appendix B. Port adaptation

With competing port authorities, for port authority i, the BRF of its own adaptation investment I_i^a to I_i^t conditional on the other port's adaptation investment I_j^a and I_j^t is as:

$$I_i^a|I_j^a, I_j^t = \frac{0.33\eta\ [(V+0.50t)\Omega - D\Psi] - 0.032\ \eta^2\Psi\left(I_j^a + I_j^t\right)}{\omega t - 0.36\ \eta^2\Psi} + \frac{0.36\ \eta^2\Psi}{\omega t - 0.36\ \eta^2\Psi}I_i^t = A + BI_i^t$$

where $A = \frac{0.33\eta\ [(V+0.5t)\Omega - D\Psi] - 0.032\ \eta^2\Psi(I_j^a + I_j^t)}{\omega t - 0.36\ \eta^2\Psi}$ and $B = \frac{0.36\ t\eta^2\Psi}{\omega t - 0.36\ \eta^2\Psi}$.

For terminal operator i, the BRF of its own adaptation investment in response to I_i^a is as,

$$I_i^t|I_j^a, I_j^t = \frac{0.16\eta\ [(V+0.5t)\Omega - D\Psi] - 0.015\ \eta^2\Psi\left(I_j^a + I_j^t\right)}{\omega t - 0.17\eta^2\Psi} + \frac{0.17\ \eta^2\Psi}{\omega t - 0.17\ \eta^2\Psi}I_i^a = C + FI_i^a$$

where $C = \frac{0.16\eta\ [(V+0.5t)\Omega - D\Psi] - 0.015\ \eta^2\Psi(I_j^a + I_j^t)}{\omega t - 0.17\eta^2\Psi}$ and $F = \frac{0.17\ \eta^2\Psi}{\omega t - 0.17\ \eta^2\Psi}$.

B and F are positive as the SOCs suggest $\omega > 0.36\ \frac{\eta^2}{t}\Psi$. The two BRFs are positively sloped, suggesting that the port adaptation investment at the same port is strategic complement. The BRFs are plotted as following Fig. A2.

As shown in above figure, if $\omega < \frac{0.48\ \Omega(V+0.5t)\eta^2}{Dt}$, the binding constraint $\eta(I_i^a + I_i^t) = D$ indicated by the orange line cuts two best response lines inside of the interior Nash equilibrium. Any point on the orange line is a Nash equilibrium, as port authority i and terminal operator i have the incentive to increase adaptation investment but already reaching constraint $\eta(I_i^a + I_i^t) = D$. Each party does not have incentive to deviate from its adaptation investment on the constraint. Thus, there are infinite Nash equilibria if the constraint $\eta\ (I_i^a + I_i^t) \le D$ is binding.

For the port authority i, the BRF to the adaptation investment of the other port authority I_j^a, conditional on two ports' terminal operators' adaptation investments is as:

$$I_i^a|I_i^t, I_j^t = \frac{0.33\eta\ [(V+0.5t)\Omega - D\Psi] + 0.032\ \eta^2\Psi\left(11I_i^a - I_j^t\right)}{\omega t - 0.36\ \eta^2\Psi} - \frac{0.032\ \eta^2\Psi}{\omega t - 0.36\ \eta^2\Psi}I_j^a = G + HI_j^a$$

where $G = \frac{0.33\eta\ [(V+0.5t)\Omega - D\Psi] + 0.032\ \eta^2\Psi(11I_i^a - I_j^t)}{\omega t - 0.36\ \eta^2\Psi}$ and $H = -\frac{0.032\ \eta^2\Psi}{\omega t - 0.36\ \eta^2\Psi}$.

For the port authority j, the BRF to the adaptation investment of that of port authority i is as:

$$I_j^a|I_i^t, I_j^t = \frac{0.33\eta\ [(V+0.5t)\Omega - D\Psi] + 0.032\ \eta^2\Psi\left(11I_j^a - I_i^t\right)}{\omega t - 0.36\ \eta^2\Psi} - \frac{0.032\ \eta^2\Psi}{\omega t - 0.36\ \eta^2\Psi}I_i^a = J + KI_j^a$$

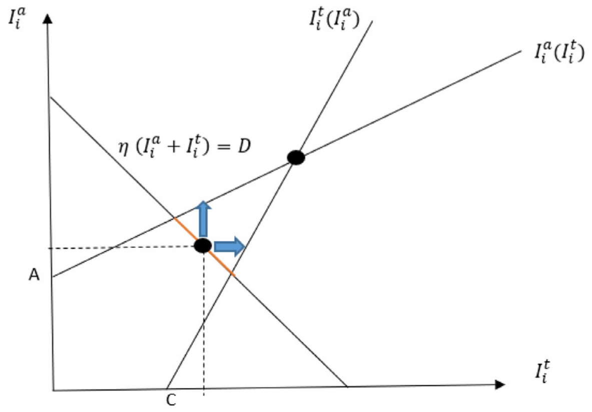

Fig. A2. The best response adaptation investment functions for port authority and terminal operators at the same port.

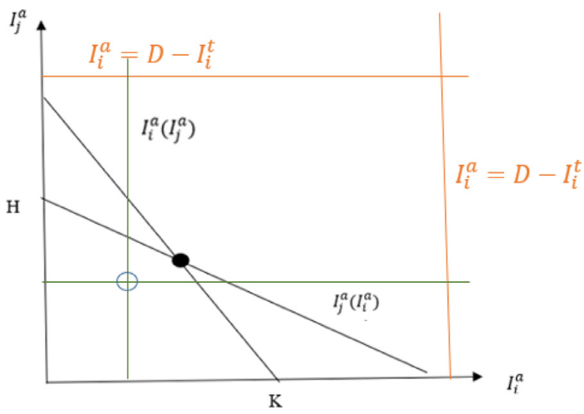

Fig. A3. The BRF of port adaptation investment for the two port authorities.

where $J = \frac{0.33\eta\ [(V+0.5t)\Omega - D\Psi] + 0.032\ \eta^2\Psi(11 I_j^a - I_i^t)}{\omega t - 0.36\ \eta^2\Psi}$ and $K = -\frac{0.032\ \eta^2\Psi}{\omega t - 0.36\ \eta^2\Psi}$.

H and K are negative as SOCs suggest $\omega > 0.36\ \frac{\eta^2}{t}\Psi$. The two BRFs are negatively sloped, suggesting that the port authorities' adaptation investments at two different ports are strategic substitutes. In addition, the condition of finite level of adaptation indicates that $\omega > 0.49\ \frac{\eta^2}{t}\Psi$. Therefore $|H| < 1$ and $|K| < 1$.

Appendix C. Comparative statics of the equilibrium adaptation to the expectation and variance of disaster occurrence probability

The expressions of $\frac{\partial \bar{I}_i^a}{\partial \Omega}$, $\frac{\partial \bar{I}_i^t}{\partial \Omega}$, $\frac{\partial \bar{I}_i^a}{\partial \Sigma}$ and $\frac{\partial \bar{I}_i^t}{\partial \Sigma}$ can be obtained as follows:

$$\frac{\partial \bar{I}_i^a}{\partial \Omega} = \frac{\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} - \left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}}{\left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)} \geq 0$$

$$\frac{\partial \bar{I}_i^t}{\partial \Omega} = \frac{\left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a}\right)\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} - \left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}}{\left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)} \geq 0$$

$$\frac{\partial \bar{I}_i^a}{\partial \Sigma} = \frac{\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} - \left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma}}{\left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)} \le 0$$

$$\frac{\partial \bar{I}_i^t}{\partial \Sigma} = \frac{\left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a}\right)\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma} - \left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}}{\left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)} \le 0$$

Taking $\frac{\partial \bar{I}_i^a}{\partial \Omega}$ and $\frac{\partial \bar{I}_i^a}{\partial \Sigma}$ as example for the proof of $\frac{\partial \bar{I}_i^a}{\partial \Omega} \ge 0$, $\frac{\partial \bar{I}_i^t}{\partial \Omega} \ge 0$ and $\frac{\partial \bar{I}_i^a}{\partial \Sigma} \le 0$, $\frac{\partial \bar{I}_i^t}{\partial \Sigma} \le 0$.

$$\frac{\partial \bar{I}_i^a}{\partial \Omega} = \underbrace{\frac{\left(\overbrace{\overbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t}}^{\ge 0} + \overbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}}^{\le 0}}^{\ge 0}\right)\overbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}}^{\ge 0} - \left(\overbrace{\overbrace{\frac{\partial^2 E[\pi_i]}{\partial {I_i^t}^2}}^{\ge 0} + \overbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}}^{\le 0}}^{\ge 0}\right)\overbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}}^{\ge 0}}{\underbrace{\left(\underbrace{\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2}}_{\le 0} + \underbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}}_{\le 0}\right)}_{\le 0}\underbrace{\left(\underbrace{\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2}}_{\le 0} + \underbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}}_{\le 0}\right)}_{\le 0} - \underbrace{\left(\underbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a}}_{\le 0} + \underbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}}_{\ge 0}\right)}_{\ge 0}\underbrace{\left(\underbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t}}_{\ge 0} + \underbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}}_{\le 0}\right)}_{\ge 0}}}_{\ge 0}$$

$$\ge 0$$

For the denominator $(\frac{\partial^2 E[\pi_i]}{\partial I_{ia^2}} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a})(\frac{\partial^2 E[\pi_i]}{\partial I_{it^2}} + \frac{\partial^2 E[\pi_i]}{\partial I_i^t \partial I_j^t}) - (\frac{\partial^2 E[\pi_i]}{\partial I_{it} \partial I_j^a} + \frac{\partial^2 E[\pi_i]}{\partial I_i^t \partial I_i^a})(\frac{\partial^2 E[\pi_i]}{\partial I_{ia} \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t})$, the second-order derivatives suggest $\frac{\partial^2 E[\pi_i]}{\partial I_{ia^2}} \le 0$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a} \le 0$, $\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} \le 0$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t} \le 0$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} \le 0$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a} \ge 0$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} \ge 0$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t} \le 0$. $|\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}| = |\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}|$ and $|\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2}| \ge |\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t}|$, $|\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2}| \ge |\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}|$ and $|\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}| = |\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}|$. Thus, it is concluded that the denominator is positive. The sign of $\frac{\partial \bar{I}_i^a}{\partial \Omega}$, therefore, depends on the sign of $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial b\Omega}$.

The proof of $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} \ge 0$ is as follows. Substituting $\tilde{I}_i^a = \tilde{I}_j^a = \frac{\eta[(2V+t)\ \Omega - 2D\Psi]}{6.7\omega t - 3\Psi\eta^2}$, $\tilde{I}_i^t = \tilde{I}_j^t = \frac{\eta[(2V+t)\Omega - 2D\Psi]}{14\omega t - 6.\Psi\eta^2}$ into $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} = \frac{\eta[0.26\omega t^2 + [(0.12\psi - 0.24\Omega^2)\eta^2 + (0.5V - 0.99D\Omega)\omega]t + (0.48\Omega^2 - 0.24\psi)V\eta^2]}{1.60\omega t - 0.75\eta^2\psi}$. The denominator of $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}$ is $1.60\omega t - 0.75\eta^2\psi > 0$. For the numerator, it is an increasing function in ω. The condition of finite level of adaptation requires $\omega > \frac{0.48\ \Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.48\ \Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} = \frac{0.16(2V+t)\eta}{t} > 0$. Therefore, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} > 0$ when $\omega \ge \frac{0.48\ \Omega(V+0.5t)\eta^2}{Dt}$.

Similarly, one can also show $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} \ge 0$. Substituting $\tilde{I}_i^a = I_j^a = \frac{\eta[(2V+t)\ \Omega - 2D\Psi]}{6.7\omega t - 3\Psi\eta^2}$, $\tilde{I}_i^t = \tilde{I}_j^t = \frac{\eta[(2V+t)\Omega - 2D\Psi]}{14\omega t - 6.\Psi\eta^2}$ into $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} = \frac{\eta[0.24(V+0.5t)(2\Omega^2 - \psi)\eta^2 + (0.5V + 0.25t - D\Omega)\omega t]}{3.2\omega t - 1.6\eta^2\psi}$, with the denominator $3.2\omega t - 1.6\eta^2\psi$ to be positive, and numerator as an increasing function in ω. The condition of finite level of adaptation requires $\omega \ge \frac{0.48\ \Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.48\ \Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} = \frac{0.15(2V+t)\eta}{t} > 0$. Therefore, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} > 0$ when $\omega \ge \frac{0.48\ \Omega(V+0.5t)\eta^2}{Dt}$.

Similarly, it can also been shown that the signs of $\frac{\partial \bar{I}_i^a}{\partial \Sigma}$ and $\frac{\partial \bar{I}_i^t}{\partial \Sigma}$ depend on $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}$. The proof of $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma} \le 0$ is as follows. Substituting $\tilde{I}_i^a = I_j^a = \frac{\eta[(2V+t)\ \Omega - 2D\Psi]}{6.7\omega t - 3\Psi\eta^2}$, $\tilde{I}_i^t = \tilde{I}_j^t = \frac{\eta[(2V+t)\Omega - 2D\Psi]}{14\omega t - 6.\Psi\eta^2}$ into $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma}$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma} = \frac{\eta[0.48(V+0.5t)\Omega\eta^2 - D\omega t]}{t(3.1\omega t - 1.5\psi\eta^2)}$. The denominator $t(3.1\omega t - 1.5\psi\eta^2)$ is positive, and the numerator is a decreasing function in ω. The condition of fi-

nite level of adaptation requires $\omega > \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma} = 0$. Therefore, $\frac{\partial^2 E[\pi_i]}{\partial I_i^t \partial \Sigma} \le 0$ when $\omega \ge \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$.

Similarly, one can also show $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} \le 0$. Substituting $\tilde{I}_i^a = I_j^a = \frac{\eta[(2V+t)\,\Omega-2D\Psi]}{6.7\omega t-3\Psi\eta^2}$, $\tilde{I}_i^t = \tilde{I}_j^t = \frac{\eta[(2V+t)\Omega-2D\Psi]}{14\omega t-6.\Psi\eta^2}$ into $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} = \frac{\eta[0.48(V+0.5t)\Omega\eta^2 - D\omega t]}{t(6.4\omega t-3.1\psi\eta^2)}$. The denominator $t(6.4\omega t - 3.1\psi\eta^2)$ is positive, and the numerator is a decreasing function in ω. The condition of finite level of adaptation requires $\omega > \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} = 0$. Therefore, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} \le 0$ when $\omega \ge \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$. Analogously, the sign of $\frac{\partial \tilde{I}_i^t}{\partial \Sigma}$ also depends on $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}$, which is negative.

The expressions of $\frac{\partial \tilde{I}_i^a}{\partial \Omega}$, $\frac{\partial\, \tilde{I}_i^t}{\partial \Omega}$ and $\frac{\partial \tilde{I}_i^a}{\partial \Sigma}$, $\frac{\partial\, \tilde{I}_i^t}{\partial \Sigma}$ can be solved as follows:

$$\frac{\partial \tilde{I}_i^a}{\partial \Omega} = \frac{\left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} - \left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial \Omega}}{\left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial {I_i^a}^2} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^t}\right)} \ge 0$$

$$\frac{\partial \tilde{I}_i^t}{\partial \Omega} = \frac{\left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a}\right)\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial \Omega} - \left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial {I_i^a}^2} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}}{\left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial {I_i^a}^2} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^t}\right)} \ge 0$$

$$\frac{\partial \tilde{I}_i^a}{\partial \Sigma} = \frac{\left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} - \left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial \Sigma}}{\left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial {I_i^a}^2} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^t}\right)} \le 0$$

$$\frac{\partial \tilde{I}_i^t}{\partial \Sigma} = \frac{\left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a}\right)\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial \Sigma} - \left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial {I_i^a}^2} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}}{\left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial {I_i^a}^2} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E\left[\pi_i+\pi_j\right]}{\partial I_i^a \partial I_j^t}\right)} \le 0$$

The proof of the signs of the above comparative statics is in the spirit of that for $\frac{\partial \bar{I}_i^a}{\partial \Omega} \ge 0$, $\frac{\partial \bar{I}_i^t}{\partial \Omega} \ge 0$, $\frac{\partial \bar{I}_i^a}{\partial \Sigma} \ge 0$ and $\frac{\partial \bar{I}_i^t}{\partial \Sigma} \ge 0$ (the detailed proof is available upon request).

The expressions of $\frac{\partial \hat{I}_i^a}{\partial \Omega}$, $\frac{\partial \hat{I}_i^t}{\partial \Omega}$ and $\frac{\partial \hat{I}_i^a}{\partial \Sigma}$, $\frac{\partial \hat{I}_i^t}{\partial \Sigma}$ can be obtained as follows:

$$\frac{\partial \hat{I}_i^a}{\partial \Omega} = \frac{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Omega} - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega}}{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)} \ge 0$$

$$\frac{\partial \hat{I}_i^t}{\partial \Omega} = \frac{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega} - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Omega}}{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)} \le 0$$

$$\frac{\partial \hat{I}_i^a}{\partial \Sigma} = \frac{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Sigma} - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma}}{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)} \ge 0$$

$$\frac{\partial \hat{I}_i^t}{\partial \Sigma} = \frac{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma} - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Sigma}}{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)} \le 0$$

The proof of the signs of the above comparative statics is in the spirit of that $\frac{\partial \bar{I}_i^a}{\partial \Omega} \ge 0$, $\frac{\partial \bar{I}_i^t}{\partial \Omega} \ge 0$, $\frac{\partial \bar{I}_i^a}{\partial \Sigma} \ge 0$ and $\frac{\partial \bar{I}_i^t}{\partial \Sigma} \ge 0$ (the detailed proof is available upon request).

Appendix D. Equilibrium adaptation investment with change in port competition intensity

The equilibrium adaptations with the competing port authorities are obtained as follows:

$\bar{I}_i^a(t') = \bar{I}_j^a(t')$

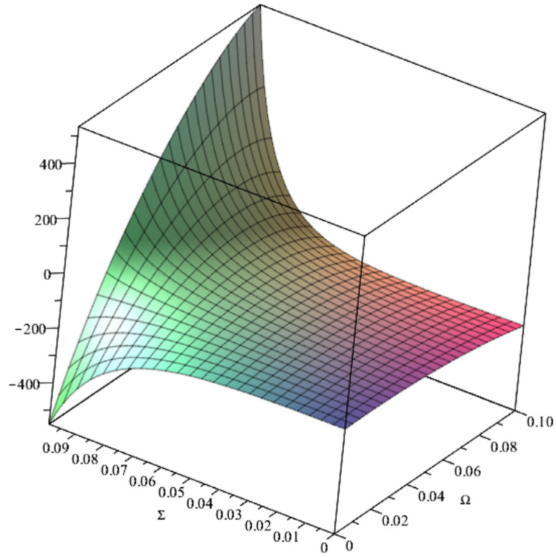

Fig. A4. Numerical values of $E[\overline{SW}_{(g)}] - E[\widetilde{SW}_{(g)}]$ as a function of Ω and Σ. *Note:* Because $\Psi = \Sigma + \Omega^2 < \Omega$, we have the constraint that $\Sigma < \Omega - \Omega^2$. In the figure, we do not impose this constraint. But even with this constraint, the values of $E[\overline{SW}_{(g)}] - E[\widetilde{SW}_{(g)}]$ is still uncertain and depends on the values of Ω and Σ.

$$= \frac{\eta\left(4t'+t\right)\left(4t'+3t\right)\left(2t'+t\right)\left(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4\right)[(2V+t)\ \Omega-2D\Psi]}{\left(4t'+3t\right)\left(4t'+t\right)^2\left(16t'^2+18t't+3t^2\right)\left(16t'^2+14t't+t^2\right)^2\omega t-8\left(6t'^2+6t't+t^2\right)\left(8t'^2+8t't+t^2\right)\left(2t'+t\right)\left(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4\right)\Psi\eta^2}$$

$$\bar{I}_i^t\left(t'\right)=\bar{I}_j^t\left(t'\right)$$
$$= \frac{\eta\left(2t'+t\right)\left(8t'^2+8t't+t^2\right)^2\left(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4\right)[(2V+t)\ \Omega-2D\Psi]}{\left(4t'+3t\right)\left(4t'+t\right)^2\left(16t'^2+18t't+3t^2\right)\left(16t'^2+14t't+t^2\right)^2\omega t-8\left(6t'^2+6t't+t^2\right)\left(8t'^2+8t't+t^2\right)\left(2t'+t\right)\left(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4\right)\Psi\eta^2}$$

The equilibrium adaptations with the monopoly port authority are obtained as follows:

$$\tilde{I}_i^a\left(t'\right)=\tilde{I}_j^a\left(t'\right)=\frac{0.25\eta\left(4t'+3t\right)\left(2t'+t\right)\left(4t'+t\right)[(2V+t)\ \Omega-2D\Psi]}{(4t'+3t)(4t'+t)^2\omega t-\left(6t'^2+6t't+t^2\right)(2t'+t)\Psi\eta^2}$$

$$\tilde{I}_i^t\left(t'\right)=\tilde{I}_j^t\left(t'\right)=\frac{0.25\eta\left(2t'+t\right)\left(8t'^2+8t't+t^2\right)[(2V+t)\ \Omega-2D\Psi]}{(4t'+3t)(4t'+t)^2\omega t-\left(6t'^2+6t't+t^2\right)(2t'+t)\Psi\eta^2}$$

In addition, the equilibrium adaptations with competing port authorities but allowing intra-port coordination can be derived as follows:

$$\hat{I}_i^a\left(t'\right)=\hat{I}_j^a\left(t'\right)=\hat{I}_i^t\left(t'\right)=\hat{I}_j^t\left(t'\right)$$
$$= \frac{\begin{bmatrix} 4\eta\left(2t'+t\right)\left(6t'^2+6t't+3t^2\right)\left(8t'^2+8t't+3t^2\right)\left(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4\right) \\ [(2V+t)\ \Omega-2D\Psi] \end{bmatrix}}{\begin{bmatrix} & \omega t- \\ \left(4t'+3t\right)\left(4t'+t\right)^2\left(16t'^2+18t't+3t^2\right)\left(16t'^2+14t't+t^2\right)^2 & 16\left(6t'^2+6t't+t^2\right)\left(8t'^2+8t't+t^2\right)\left(2t'+t\right) \\ & \left(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4\right)\Psi\eta^2 \end{bmatrix}}$$

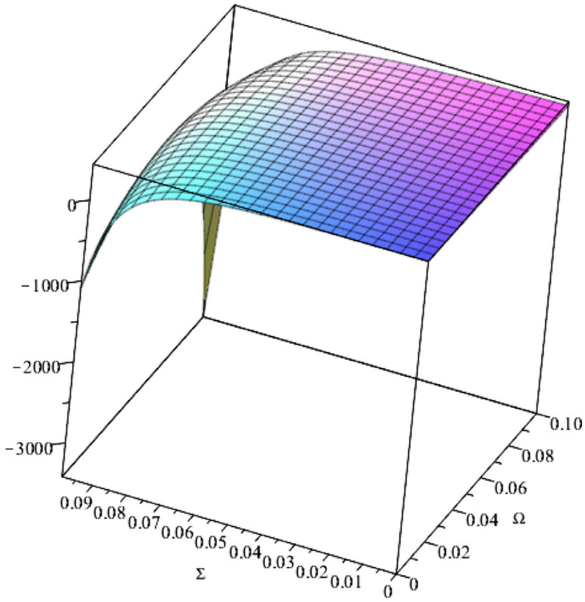

Fig. A5. Numerical values of $E[\overline{SW}_{(g)}] - E[\widehat{SW}]$ as a function of Ω and Σ. *Note:* Because $\Psi = \Sigma + \Omega^2 < \Omega$, we have the constraint that $\Sigma < \Omega - \Omega^2$. In the figure, we do not impose this constraint. But even with this constraint, the values of $E[\overline{SW}_{(g)}] - E[\widehat{SW}]$ is still uncertain and depends on the values of Ω and Σ.

Appendix E. Numerical simulation of the expected social welfare with public port authorities

For the ports with public port authorities, the expected welfare does not necessarily increase with the adaptation investments. In other words, despite $\bar{I}^a_{(g)i} > \tilde{I}^a_{(g)i}$ and $\hat{I}^a_{(g)i}$, it is not necessary to observe that $E[\overline{SW}_{(g)}] > E[\widetilde{SW}_{(g)}]$ and $E[\widehat{SW}_{(g)}]$.

A numerical simulation is conducted for values of $E[\overline{SW}_{(g)}] - E[\widetilde{SW}_{(g)}]$ and $E[\overline{SW}_{(g)}] - E[\widehat{SW}_{(g)}]$. For $E[\overline{SW}_{(g)}] - E[\widetilde{SW}_{(g)}]$, we assign $V = 10$, $D = 7$, $\omega = 25$, $t = 0.1$ and $\eta = 2$. Then, $E[\overline{SW}_{(g)}] - E[\widetilde{SW}_{(g)}]$ is a function of the expectation Ω and the variance Σ of the disaster occurrence probability. We plot the simulated values of $E[\overline{SW}_{(g)}] - E[\widetilde{SW}_{(g)}]$ as a function of Ω and Σ. We set $\Omega \in [0, 0.01]$ and $\Sigma \in [0, 0.099]$ to reflect the fact that the disaster occurrence is a small chance event. With our assigned parameter values, this chosen range of Ω and Σ satisfies the SOC, finite level of adaptation and interior solution conditions. As shown in Fig. A4, we can observant that $E[\overline{SW}_{(g)}] - E[\widetilde{SW}_{(g)}]$ can either be positive or negative.

Analogously, the numerical simulation shows that $E[\overline{SW}_{(g)}] - E[\widehat{SW}_{(g)}]$ can also be positive or negative, depending on the values of Ω and Σ as well.

It is also found that the public port authorities do not always lead to a higher expected welfare compared to private port authorities. For example, the competing public port authorities can result in a lower expected welfare $E[\overline{SW}_{(g)}]$ than that of the competing private port authorities with intra-port coordination $E[\widehat{SW}]$. A numerical simulation of $E[\overline{SW}_{(g)}] - E[\widehat{SW}]$ with $V = 10$, $D = 7$, $\omega = 14$, $t = 0.1$ and $\eta = 2$ was also conducted. $E[\overline{SW}_{(g)}] - E[\widehat{SW}]$ is a function of Ω and Σ. We plot the values of $E[\overline{SW}_{(g)}] - E[\widehat{SW}]$ as a function of Ω and Σ in Fig. A5, by setting $\Omega \in [0, 0.01]$ and $\Sigma \in [0, 0.099]$. It can also be observed that $E[\overline{SW}_{(g)}] - E[\widehat{SW}]$ can either be positive or negative.

Appendix F. Proof of $E(C_i|\, n)$ with Poisson jump disaster occurrence at the operation stage

Conditional on $N(\bar{T}) = n$, we have:

$$\sum_{r=1}^{n} E\left(U_{(r)}|n\right) = \sum_{r=1}^{n} \frac{r}{n+1} = \frac{n}{2}$$

and,

$$\sum_{r=1}^{n} E\left({U_{(r)}}^2|n\right) = \sum_{r=1}^{n} \left\{\left[E\left(U_{(r)}|n\right)\right]^2 + Var\left(U_{(r)}|n\right)\right\} = \sum_{r=1}^{n} \left[E\left(U_{(r)}|n\right)\right]^2 + \sum_{r=1}^{n} Var\left(U_{(r)}|n\right) = \sum_{r=1}^{n} \left(\frac{r}{n+1}\right)^2 + \sum_{r=1}^{n} \frac{r(n-r+1)}{(n+2)(n+1)^2} = \frac{\sum_{r=1}^{n} r^2}{(n+1)^2} + \frac{\sum_{r=1}^{n} r(n-r+1)}{(n+2)(n+1)^2} = \frac{n}{3}$$

Substituting the $\sum_{r=1}^{n} E(U_{(r)}|n) = \frac{n}{2}$ and $\sum_{r=1}^{n} E({U_{(r)}}^2|n) = \frac{n}{3}$ into Eq. (14), we obtain:

$$E(C_i|\ n) = \left(D - \eta\left(I_i^a + I_i^t\right) - \tfrac{1}{2}\beta\bar{T}\right)\bar{T}n - \left(D - \eta\left(I_i^a + I_i^t\right) - \beta\bar{T}\right)\bar{T}$$
$$\sum_{r=1}^{n} E\left(U_{(r)}|n\right) - \tfrac{1}{2}\beta {U_{(r)}}^2\bar{T}^2 \sum_{r=1}^{n} E\left({U_{(r)}}^2|n\right) = \tfrac{1}{6}n\bar{T}\left\{\left(3D - \beta\bar{T}\right) - 3\eta\left(I_i^a + I_i^t\right)\right\}$$

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